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# Hydrograph development for agricultural watersheds based on point rainfall records

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PALMER, David B., 1927-  
HYDROGRAPH DEVELOPMENT FOR AGRI-  
CULTURAL WATERSHEDS BASED ON POINT  
RAINFALL RECORDS.

Iowa State University of Science and Technology  
Ph.D., 1962  
Engineering, agricultural

University Microfilms, Inc., Ann Arbor, Michigan

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HYDROGRAPH DEVELOPMENT FOR AGRICULTURAL WATERSHEDS  
BASED ON POINT RAINFALL RECORDS

by

David B. Palmer

A Dissertation Submitted to the  
Graduate Faculty in Partial Fulfillment of  
The Requirements for the Degree of  
DOCTOR OF PHILOSOPHY

Major Subjects: Agricultural Engineering  
Civil Engineering

Approved:

Signature was redacted for privacy.

In Charge of Major Work

Signature was redacted for privacy.

Heads of Major Departments

Signature was redacted for privacy.

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1962

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## INTRODUCTION AND OBJECTIVES

Recent developments in the application of hydrology to small agricultural watersheds have laid the ground work for improved estimates of runoff. Interest in such estimates has increased over the last two decades as a result of the watershed approach to the solution of the physical problems of soil and water conservation. Improved estimates are needed by the designer of small hydraulic structures such as spillways, channels, road culverts, drop inlets, and stilling basins.

Development of the infiltration theory of runoff has made possible a rational approach to the problem of predicting the time-distribution of rainfall excess resulting from a specified precipitation pattern occurring on a land area of specified soil, cover, and condition. Recent studies have developed procedures for synthesizing unit hydrographs for small agricultural watersheds. The modern digital computer provides a means by which rainfall excess patterns may be readily routed through a unit hydrograph, thereby predicting the resulting time-distribution of runoff.

The physical problems of soil and water conservation represent one part of a triad of problems. Criteria for economic soundness and institutional permissiveness must also be satisfied before constructive solutions can develop.

Economic soundness and the available range of physical possibilities are often linked together by the concept of a recurrence interval. Economic consideration determines what recurrence interval is appropriate and physical conditions establish associated design criteria, for example, pertinent runoff quantities.

One of the major design limitations is the lack of an adequate association between recurrence interval and the runoff quantity pertinent to the design of soil and water conservation facilities. It is this area that the present study explores. The objectives are:

1. To develop procedures
  - a. For combining intensity-time rainfall records with standard infiltration-capacity curves to obtain a time-distribution record of rainfall excess production,
  - b. For synthesizing unit graph ordinates according to one of the available methods, and
  - c. For routing time-distribution records of rainfall excess production through a unit graph in order to predict time distributions of surface runoff.
2. To predict peaks and volumes of surface runoff to be expected from a small agricultural watershed for any specified recurrence interval when the watershed

is located in a region with physiographic characteristics similar to the Marshall soil association of western Iowa.

## REVIEW OF LITERATURE

The prediction of surface runoff rates and volumes starts with the relationship:

$$\text{Runoff} = \text{Rainfall} - \text{Infiltration losses} - \text{Initial losses} \quad (1)$$

Application of this general surface runoff equation varies with size and characteristics of the watershed being considered and the time increment which is selected. For small agricultural watersheds the infiltration theory of runoff and the unit hydrograph principle are generally accepted as the best tools available for solving the runoff equation. Solutions for a point are, in general, more satisfactory than when the equation is applied to an area. A small agricultural watershed is one on the order of ten square miles or less in area, the major portion of which is devoted to the production of agricultural crops.

## Rainfall

Several questions concerning the precipitation received by a watershed are pertinent to the prediction of surface runoff. One involves selecting the storms which are critical for design purposes. On small agricultural watersheds, the relatively short-duration, high-intensity storms will produce



the large runoff quantities. In a study where actual storm records are to be used to predict runoff, there would be no point in including the relatively long-duration, low-intensity storms. One possible criterion for storm selection is to exclude all storms which do not meet the U. S. Weather Bureau's definition of an "excessive storm", i.e.,

$$d \geq 0.01 t + 0.20 \quad (2)$$

in which  $d$  is in inches and  $t$  is in minutes (55). A storm is classified as "excessive" if it meets this criterion for one or more of the following time periods: 5, 10, 15, 20, 30, 45, 60, 80, 100, 120, 150, and 180 minutes.

Another question concerns the effect of precipitation which occurs in the period antecedent to the runoff-producing storm, i.e., change in soil moisture content and compaction of the soil surface. Linsley, Kohler, and Paulhus (32) suggest using an antecedent-precipitation index, API, of the form

$$API = \sum_{i=0}^n q^i I_i \quad (3)$$

in which  $i$  = the number of days prior to the runoff-producing storm that the antecedent precipitation occurred,  $I$  = the antecedent precipitation in inches,  $n$  = the number of days to be considered for the index, and  $q$  = a constant ranging from 0.85 to 0.90 for most of the eastern and central portions of

the United States. They suggest 6 to 10 days for  $n$  for certain stream flow studies. In an application of the infiltration theory, Brakensiek (5) used  $n = 7$  and  $q = 0.8$ .

A third question concerns the use of point rainfall records to represent precipitation over an area. Studies of rainfall records have shown that the average intensity over an area in relation to the maximum point rainfall in that area is some inverse function of the size of that area (57). However, U. S. Weather Bureau studies of 20 dense networks (57) have shown considerable scatter in this relationship. Other conclusions of these studies have been: 1) the area-depth relationship varies with duration, i.e., the greater the duration, the more nearly a point rainfall record approximates the average areal depth, 2) the area-depth relationship seems to be independent of geographic location and time of year, and 3) storm magnitude is not a parameter in the area-depth relationship.

Linsley and Kohler (31) studied two years of daily totals of precipitation from a 55-gage network covering an area about 10 by 22 miles. Their findings included: 1) the absolute deviations (in inches) of individual gage records from the 55-gage average were a function of precipitation amount, and in terms of the percentage deviations, the greater the precipitation amount, the smaller the percentage deviation, 2) the gage centrally located gives, on the average,

the best measure of areal precipitation when compared with any other gage location, and 3) the deviations both of individual stations and group averages from the 55-station mean decrease markedly when averages for longer than daily periods are considered.

An expression of the form

$$Y = a + bX^{1/2} \quad (4)$$

where Y is the average rainfall depth in inches, X is the area enveloped in square miles, and a and b are constants, was proposed by Huff and Stout (25) to relate area and depth of rainfall. Their results were based on the analysis of from 18 to 28 storms on each of three watersheds. The watersheds ranged in size from 5.2 to 280 square miles.

Later, Huff and Neill (24), in a study of six years of data from individual storms occurring on seven rain-gage networks in Illinois, found the deviation, E, between areal mean rainfall and point observation, P, at areal center to be empirically described by

$$\log E = -2.011 + 0.54 P^{0.5} + 0.29 \log A \quad (5)$$

in which E and P are in inches and the area, A, is in square miles. As an example, assume  $A = 7.65$  square miles and  $P = 6$  inches:  $E = 0.369$  and the average precipitation over the area = 5.631 inches or 6.15% less than the point observation.

From a study of the records of storms which occurred in 1952-53, Huff and Neill found very little change in the time distribution of rainfall with increasing area (23, p. 7):

For example, 50 percent of the point rainfall was found to occur during 10 percent of the time it is raining. At 25 square miles, 50 percent of the areal mean rainfall occurs in 11 percent of the time, while for 100 squares miles 50 percent occurs in 12 percent of the time.

Thus, it is variation in depth of rainfall over an area and not variation in the time distribution of this rainfall which presents the problem in using point rainfall data over a watershed.

In a study of the distribution of excessive rainfall amounts over an urban area, Huff and Changnon (22) concluded that a point rainfall record is a satisfactory index of the areal mean rainfall frequency distribution in a 10-square mile area.

A fourth question concerns the effect of intensity pattern on runoff. Smith and Crabb (49), in a study of 11 years of rainfall data from East Lansing, Michigan, investigated the relations between class, pattern, and total of storm rainfall and resulting runoff under cultivated conditions. They found amount of storm rainfall to be of more significance in producing runoff than intensity.

A fifth question involves the use of the station-year technique to the analysis of rainfall. Linsley, Kohler, and

Paulhus give the following description (32, p. 560):

The method assumes that records from several stations in a limited area can be combined and treated as a single record whose length is equal to the sum of the individual records. The basic assumption is that the frequency curves of the individual stations would be identical if a sufficient period of record existed. This means that the entire area from which the stations are selected must be meteorologically homogeneous.

They further suggest that 1) ten years of independent record should be considered as a minimum for analysis and 2) if the stations are so spaced that one and only one station measures each storm, then the data are wholly independent. They further note that fortunately, the higher, short-period amounts are usually the result of intense, small-area thunderstorms, and the dependence between stations is fairly low.

### Infiltration

For most excessive storms the major "loss" is infiltration which Cook (7) defines as (7, p. 727) "the passage of water through the surface of the soil into the soil mass". R. E. Horton receives major credit for initiating some understanding of the infiltration process; his definitive publications during the 1930's (19) and early 1940's (20) have been a guide to investigations since that time. Cook (7), in a

report of the Section on Hydrology of the American Geophysical Union, published an excellent review of the current thinking on infiltration which strongly embraced Horton's ideas. Horton proposed (19) and later derived (20) an expression for predicting infiltration rate,  $f$ , at any time,  $t$ , of the form (20, p. 401),

$$f = f_c + (f_o - f_c) e^{-kt} \quad (6)$$

in which  $f_o$  and  $f_c$  are the initial and constant infiltration rates,  $e$  is the base of the Napierian logarithms, and  $k$  is a constant which was thought by Horton to vary with the energy of falling rain.

Even though many investigators have worked on various aspects of infiltration, only two additional references to fairly recent work will be mentioned here. During the 1950's Philip (37-43) presented a set of seven papers in which he used moisture diffusion theory in a comprehensive analytical study of water infiltration. Green (15) has given an excellent summary of previous infiltration work and then gone on to investigate the effect of antecedent soil moisture by applying moisture diffusion theory to both field and laboratory measurements. From studies on Ida and Grundy soils he found (15, p. 126)

. . . that in some cases antecedent moisture differences on a given soil may influence infiltration

rates as much as tillage, surface sealing, or profile differences between soils.

A paper by Brakensiek and Frevert (4) is particularly germane to the present study. In it they reported on a portion of the work that was completed in an earlier study (5). A procedure was developed for fitting Horton's infiltration equation (20) to Type F infiltrometer data and evidence was presented showing that rainfall rates minus runoff rates are essentially infiltration rates. In the process Brakensiek (5) derived and evaluated the constants of equations to predict the parameters of Horton's infiltration equation for the Marshall silt loam soil in combination with corn, small grain, and legume-grass covers. The 7-day antecedent precipitation index, API, computed with a constant of 0.8 is the only independent variable in these parameter prediction equations.

Brakensiek and Frevert suggest that their results can be used as follows (4, p. 76):

. . . in estimating the surface runoff for an actual watershed situation, the following steps are required:

i) Delineate the soil-crop areas of the given watershed. In this study the Marshall silt loam-crop complexes are depicted.

ii) Develop the potential infiltration curve for each complex. For this study the 7-day antecedent precipitation index (API) as calculated from rainfall records specifies the complex's infiltration capacity curve.

iii) Estimate the runoff that the given

rainfall would produce on each complex. This requires that the derived infiltration capacity curve, for each complex, be superimposed on the given rainfall histogram. The difference between these two curves, the so-called rainfall excess, would then be corrected for initial abstractions and depression storage.

iv) Combine the individual complex runoff volumes, weighted by the size of each complex, to give watershed surface runoff.

Another concept of the infiltration process has been set forth by Holtan (18). He estimates a potential volume of infiltration from characteristics of the soil and then provides an equation which describes progress toward this volume. The extent to which the available porosity, i.e., the potential volume, is exhausted, before the rate of infiltration becomes constant, appeared to be a function of the type of vegetation present. A vegetation index, basal area, was used to predict the extent to which available storage is utilized before the rate of infiltration becomes constant. Basal area is the percentage of ground surface area occupied by roots or stems. Assuming that the capacity rate of infiltration is a function of the unoccupied porosity at a particular time an expression for infiltration rate was established as

$$f = 0.62 k S_r^{1.387} + f_c \quad (7)$$

in which  $f$  = rate of infiltration in inches per hour,  $k$  = vegetative factor,  $S_r$  = available porosity as depleted by



infiltrated volumes in inches, and  $f_c$  = final constant rate of infiltration in inches per hour. Holton's infiltration concept offers another possibility for realistically accounting for infiltration losses in the runoff process.

Certain deficiencies have been noted by investigators in the application of infiltration theory to the problem of estimating storm runoff. For example, Kohler and Linsley, writing on river flood forecasting, note 1) that (27, p. 1) ". . . the hydrologic characteristics of a natural basin exceeding a few acres in area are so variable as to make such a rational approach exceedingly complex" and 2) that in such forecasting (27, p. 1) "time is not available for the detailed consideration of large basins by the rational infiltration approach". These deficiencies are of lesser import to the usual requirements for runoff predictions from small agricultural watersheds.

### Initial Losses

The initial losses of the general surface runoff equation encompasses interception and depression storage. Linsley, Kohler, and Paulhus (32) add evaporation during precipitation when they define surface retention to include interception, depression storage, and evaporation during precipitation.

Langbein and Iseri (30) define interception as the amount of rain or snow stored on leaves and branches and eventually evaporated back to the air. It equals the precipitation on the vegetation minus stem flow and throughfall.

Horton (21) suggested empirical relations for evaluating interception in which cover, height of the plants, and depth of storm precipitation were the independent variables. However, the relations were based on limited experimental data from relatively small storms, and therefore, are not applicable for large storms. Based on a one-inch storm, representative values obtained were:

<u>Cover</u>	<u>Height, ft.</u>	<u>Interception, in.</u>
Corn	6	0.036
Meadow grass	1	0.085
Small grains	3	0.165

Considerable additional work on measuring interception for various forest covers has been done (47, 52) but little information is available on the more common field crops of the Midwest.

Langbein and Iseri define depression storage as (30, p. 7) "the volume of water contained in natural depressions in the land, such as puddles". There are no good measurements of depression storage available.

Brakensiek (5), in a study of infiltration rates of the Marshall silt loam soil of western Iowa, made the following

proposal for combined interception and depression storage:

Table 1. Surface retention values in inches

Crop	<u>Antecedent conditions</u>		
	Wet	Medium	Dry
Corn and small grain before mid-June	0.07	0.15	0.25
Small grain after mid-June	0.15	0.20	0.30
Grass-legume	0.20	0.25	0.25

Linsley, Kohler, and Paulhus suggest that the combined losses of interception, depression storage, and evaporation during precipitation (32, p. 260) "may be of sizable magnitude, ranging from 0.5 to 1.5 inches for cultivated fields, grasslands, and forests".

#### Runoff and Its Distribution

Since surface runoff is residual, or "rainfall excess", after the losses have been deducted from rainfall, the accuracy with which it is predicted is a measure of the validity of all intermediate assumptions and procedures.

### The unit graph

The pioneering work of Sherman (48) and his intellectual descendents in the development of the unit hydrograph concept must be given credit for much of the current thinking in hydrology. Gray (14) gave an excellent summary of this development and some of the problems that had to be resolved as the concept developed.

The unit graph for a particular watershed is derived in one of two ways. It can be empirically determined from one or more actual storm runoff records or it can be synthetically determined. In the latter method one or more watershed and/or storm parameters are used to establish the unit graph ordinates. The validity of any specific synthetic method is, in general, based upon the accuracy with which the empirical graph of a watershed is reproduced.

The work of Bender and Roberson (2) is one example of synthetic unit graph derivation. A trial-and-error method of developing unit hydrographs from long-period storms by making use of a general dimensionless unit hydrograph was presented. The watersheds involved ranged in size from 35 to 211 square miles. The general dimensionless unit hydrograph, which was developed from the unit graphs of 19 streams in the Willamette Valley in Oregon, was then used to derive unit hydrographs on streams of the area for which data were lacking for deriving unit hydrographs by the normal procedure. The IBM 650

computer was programmed to assist in making the derivations.

Gray's synthetic unit graph (14)

The existence of mathematical models for the hydrograph was shown by Edson (8) and Nash (35). Gray (14) showed these models to be of the same form as the two-parameter Gamma distribution (14, p. 49),

$$f(x) = \frac{N (\gamma)^q}{\Gamma (q)} e^{-\gamma x} x^{q-1} \quad (8)$$

in which  $f(x)$  is any "ordinate" value;  $x$  is any "x" value;  $N$  represents total frequency or number of observations of  $x$ ;  $q$  and  $\gamma$  are shape and scale parameters, respectively;  $\Gamma$  denotes the Gamma function; and  $e$  is the base of natural logarithms. In a study of 42 watersheds in the Midwest Gray (14) was able to relate the parameters of the Gamma distribution to certain watershed characteristics. In dimensionless graph form, Equation 8 appears as (14, p. 53)

$$Q_{t/P_R} = \frac{25.0(\gamma')^q}{\Gamma(q)} (e^{-\gamma' t/P_R}) (t/P_R)^{q-1} \quad (9)$$

in which  $Q_{t/P_R} = \% \text{ flow}/0.25 P_R$  at any given  $t/P_R$  value;  $\gamma' =$  dimensionless parameter equal to the product,  $\gamma P_R$ ; and  $q$ ,  $\Gamma$ , and  $e$  have the same meaning as in Equation 8.

In practical applications the parameters of Equation 9

were evaluated in the following manner. From theoretical considerations it was shown that (13, p. 42)

$$q = 1 + \gamma' \quad (10)$$

From experimental considerations it was found that (13, p. 44)

$$P_R/\gamma' = a (L/S_c)^b \quad (11)$$

in which  $L$  = length of main stream in miles,  $S_c$  = slope of the main stream in %, and  $a$  and  $b$  depend on the geographical region of the Midwest selected. For the Nebraska-western Iowa loessial area where the stream channels are in the form of deeply entrenched, "U"-shaped gullies,  $a$  was found to be 7.40 and  $b$  to be 0.498. In addition, the storage factor,  $P_R/\gamma'$ , was experimentally related to the period of rise,  $P_R$ , by (13, p. 47)

$$P_R/\gamma' = 1/(2.676/P_R + 0.0139) \quad (12)$$

### Runoff Frequency

Mean recurrence interval has been the most popular parameter for specifying the magnitude of a particular hydrologic event. When applied to floods its computation has been based on either an annual series or a partial duration series. For the annual series a tabulation is made which includes the largest event of each year of record.

For the partial duration series all events larger than some arbitrarily selected cut-off value are included.

Langbein (29) made a theoretical analysis relating the two series. He showed (20, p. 879)

. . . that for equivalent floods, the recurrence intervals in the partial-duration series are smaller than in the annual-flood series, but that the difference becomes inconsequential for floods greater than about five-year recurrence interval.

Another point of discussion in recent years concerned the "best" plotting position for items of the series. Contributors to this discussion included Chow (6), Mockus (34), and Benson (3). The theoretical distribution of such a series was also reviewed by Chow (6) and Benson (3).

Thom (51) has pointed out that mean recurrence interval, as has been quite commonly computed, is perhaps, not as valuable a statistic as has been generally assumed. In his application of a time interval distribution for excessive rainfall he developed a procedure for assigning probabilities of occurrence to specific events for any time interval. Similarly, the designer who has the population of events available to him can select the probability and time interval and then compute the corresponding magnitude of event. It appears that populations of runoff peaks and volumes would be amenable to the same procedure.

Gumbel (16) linked return period to the calculated risk

in order to obtain the value of the variable (peak runoff rate, for example) to be used in the design of a structure. His procedure would indicate the following to be approximately true: To have a 0.9 probability that a structure will last 10 years, build it to handle a 107-year recurrence interval storm. In conclusion Gumbel states that (16, p. 280)

The calculated risk should replace the arbitrary safety factors which are now used by the engineers and for actuarial calculations, balancing the cost of a structure against the risk involved. These methods lead to an appraisal of the priority of programs and to criteria basing the feasibility of projects on a given upper bound to the cost.

#### Computer Application

The electronic digital computer is admirably suited to many problems of hydrology. This is true for two related reasons. One, computers can quickly process data according to many different sets of assumptions with each set including many restrictions. The fact that hydrology is not an exact science means that the hydrologic investigator, in his attempts to find an acceptable solution, may need to process the available data according to one or more such sets. The present study is typical in this respect. Two, the relatively short period of time during which hydrologic data has been collected--seldom for more than 75 years in this country--has produced a mass of numerical values. The high-speed operation



of the computer has made possible studies which would be economically impossible if hand computations were required.

In addition to problems of sedimentation and water resources, requirements, and utilization, Swain and Riesbol suggested three areas of flood hydrology which would lend themselves to computer applications (50, p. 23):

To evaluate flood magnitudes and frequencies in terms of observed hydrologic, meteorologic, and physiographic data for specified streams or areas.

To route floods through streams, lakes, and reservoirs or combinations thereof.

To forecast flood runoff using meteorologic, hydrologic, and physiographic data.

Harbeck and Isherwood (17) reported in 1959 that the U. S. Geological Survey was analyzing published streamflow data and was starting to record basic streamflow data in digital form on paper tape for immediate processing.

Rockwood (46) and Northrop and Timberman (36) described computer programs which were developed for streamflow routing on the Columbia Basin and the Kansas River, respectively.

## INVESTIGATIONS, RESULTS, AND DISCUSSION

In order to meet the objectives of the study, investigations were made on the prediction of runoff volumes, the prediction of runoff distribution, and a frequency analysis of peak runoff rates and volumes. Throughout this report the terms "runoff volume" and "runoff depth" will be used almost interchangeably since the volume is readily attainable from the depth by multiplying by the area of the watershed. The bulk of the data reduction was accomplished by the CYCLONE, a binary electronic computer with 16,384 words of magnetic core storage. Actual communication with the computer was accomplished by punched paper tape through the "interpretive" program, EERIE.

## Prediction of Runoff Volumes

Infiltration theory permits the prediction of runoff depth for a given rainfall event without reference to the size of watershed involved. Size must be specified before estimates of peak runoff rates and volumes of runoff can be made.

### Watershed selection

The Spring Valley Creek Watershed, a 7.65-square mile area near Tabor in southwestern Iowa was selected for use. Considerable interest in this watershed had developed concerning the economics of soil and water conservation measures. Landgren (28) and Gray (12) pursued certain specified aspects of the problem.

The Spring Valley Creek Watershed was selected for several reasons. 1) It was assumed to be in the same meteorologically homogeneous area as the three U. S. Weather Bureau stations which were used as the source of precipitation data. 2) The predominant soil type is Marshall silt loam, the same type as used by Brakensiek (4) in his derivation of the constants for Horton's infiltration equation (20). 3) The watershed falls within the area of application (size and geographical location) of Gray's method (14) for predicting unit graph ordinates.

### Precipitation data selection and processing

The U. S. Weather Bureau (55) records and publishes the so-called "excessive" precipitation data for several locations in Iowa and in each of the surrounding states. Even though no rational basis is available for selecting this definition as the criterion for storm selection, it was felt from experience with storm and runoff records on small

watersheds that the definition would insure the inclusion of all storms pertinent to the study. It was also recognized that many excessive storms would give insignificant amounts of runoff from such watersheds. In Iowa such data are presently being published for the airport stations at Burlington, Des Moines, Dubuque, and Sioux City. Such data are also available for Davenport and the Omaha, Nebraska airport.

It was assumed that the recorded point rainfall amounts occurred simultaneously over the entire watershed area. The U. S. Weather Bureau (56), in a summary of area-depth studies, states that "for drainage areas larger than a few square miles consideration must be given not only to point rainfall, but to the average depth over the entire drainage area". Their work showed storm duration to be the major parameter. Interpretation of their graphical summary produced the following percentages of point rainfall appropriate to use for a watershed area of 7.65 square miles:

<u>Storm duration</u>	<u>Percentage of point rainfall for given area</u>
30 minutes	94
1 hour	97
3 hours	98
6 hours	98.5
24 hours	99

Thus, the error in estimates resulting from this assumption is considered to be relatively insignificant.

After identification of the excessive storms at the

pertinent stations, microfilmed copies<sup>1</sup> of the actual recording rain gage charts were obtained from the U. S. Weather Bureau. Processing of these charts consisted of picking off values of accumulated time and accumulated precipitation at each point of significant change in intensity. These values were then used in the computation of the rainfall excess amounts.

In addition the 7-day API was computed for each of the excessive storms. The API was used to define the parameters of the appropriate infiltration rate and mass curves.

Excessive precipitation data from three U. S. Weather Bureau stations were used in this study. The stations and the periods of record which were included are:

<u>Station</u>	<u>Period</u>	<u>Years</u>
Des Moines, Iowa	1897-1960	64
Omaha, Nebraska	1893-1960	68
Sioux City, Iowa	1907-1960	54
Total number of years		186

A total of 1091 excessive storms were recorded at these three stations during these periods. Of these 1091, there were 996 storms that were used for prediction. Forty-four storms were overlapped with another of the 996, i.e., 44 of the 996 storms actually contained 2 or more excessive storm periods

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<sup>1</sup>On file in the Agricultural Engineering Department, Iowa State University of Science and Technology, Ames, Iowa.

as classified by the U. S. Weather Bureau. Microfilmed copies of the rain gage records for 51 storms were not supplied by the Weather Bureau.

These particular stations were selected for three reasons: 1) They are close enough to each other that it was felt that an event which occurred at any one could also have occurred at either of the other two. Thus, the effective period of record was considered to be the sum of the three individual periods or a total of 186 years. 2) The stations are far enough removed from one another that it could be assumed that a storm occurring at any one could be considered to be independent of storms occurring at the other two. This is the basis for the station year assumption of 186 years of record. Associated with the transposition of storms are questions of change in shape and orientation of the isohyetal pattern. Linsley, Kohler, and Paulhus (32, p. 595) state that "for small basins in flat terrane where the governing storms are largely thunderstorms, almost any change in orientation or shape is permissible". It was assumed for this study that orientation would not be a problem due to the small size of the watersheds. 3) All three stations are reasonably close to the soil association area to which the constants of the infiltration data apply and to the watershed which was used for development of the procedure.

The format that was used for the preparation of the

precipitation data for use by the computer program is included in Appendix A. The format has three parts: 1) identification numbers (U. S. Weather Bureau station designation, month, day, and year of storm, and the 7-day antecedent precipitation index), 2) alternate entries of accumulated time (minutes) and accumulated depth (inches), and 3) a minus one which served as a termination signal to the computer program.

### Losses

The component losses from rainfall are interception, depression storage, evaporation during precipitation, and infiltration. For the runoff prediction purposes of this study only infiltration was evaluated and deducted from rainfall. Primarily this acknowledged the lack of data required for quantification of the three losses not considered. However, any or all would have a negligible effect upon the runoff from the larger storms.

Another loss which has not been previously mentioned and which may have significant influence upon runoff is seepage into the stream channel. Examples of such losses are quite commonly known for larger streams and rivers. The Dakota artesian system is an example. It crops out and absorbs water along the flanks of the Rocky Mountains, Big Horn Mountains, and Black Hills, and underlies large parts of

Kansas, Nebraska, the Dakotas, Wyoming, Montana, and Saskatchewan (33).

Allis (1) compared storm runoff volumes from small, single-crop watersheds and from a larger, mixed-crop watershed. His comparison was pertinent to the present study in two ways. 1) He found that (1, p. 223)

Direct area runoff from small watersheds can be expanded to runoff from a larger, complex watershed . . . within practical limits.

The present study has extended this technique by predicting runoff volumes from a several square mile watershed from point infiltration estimates. 2) Allis concluded that (1, p. 223)

On the average . . . there was about 13.6 percent less measured flow than computed flow [for the larger, mixed-crop watershed and that] . . . these differences are considered due mainly to transmission losses to valley alluvium . . .

He also noted that the transmission losses appeared to vary somewhat throughout the growing season. These losses in transit, or transmission losses, were not considered in the quantitative predictions of the present study. Transmission losses probably would be more important on small storm runoff predictions than on large storm predictions since a larger percentage of the runoff from small storms would be lost in this manner.

Infiltration losses were accounted for by use of the



Horton (20) infiltration equation. The work of Brakensiek and Frevert (4) provided parameter prediction equations for evaluating the three constants of the Horton equation.

Parameter prediction equations were given for the three cover conditions, corn, small grain, and legume-grass, with the 7-day API as the only independent variable. Consequently, for each storm the runoff prediction procedure to be described herein includes the computation of infiltration based on the API of that particular storm.

#### Volume prediction procedure

Rainfall excess or excess rain is defined as (26, p. 593) "that rainfall which fell at a rate greater than the rate of infiltration". This is the meaning adopted for the present study, i.e., infiltration was the only loss deducted from rainfall. In order to compute the time distribution of rainfall excess generation, the procedure used for each time increment was to 1) note the quantity of rainfall received, 2) compute the amount of infiltration that occurred during the time increment, and 3) find the difference between rainfall and infiltration. Where the quantity, rainfall minus infiltration, was positive, the difference represented the quantity of rainfall excess; where negative, there was no rainfall excess.

One problem in the use of this procedure concerned the

effect upon infiltration of quantities of rainfall received at rates less than the capacity rate of infiltration. Such quantities of rainfall are quite generally received during the initial stages of a storm and also are often received during intermediate stages, i.e., when the rainfall intensity is temporarily reduced to less than the infiltration rate and then later increases again to some value greater than the infiltration rate. Cook (7) has shown a graphical procedure which has been adopted by at least one investigator (5). No examples are known where this variation of infiltration capacity under low intensities has been mathematically computed according to the procedure outlined by Cook. An iterative solution to the problem of predicting variation of infiltration capacity under low intensities is possible and was utilized herein.

The procedure for obtaining increments of rainfall excess follows. Figures 1 and 2 are graphical representations of the procedure.

Given

1. Equation of infiltration capacity,

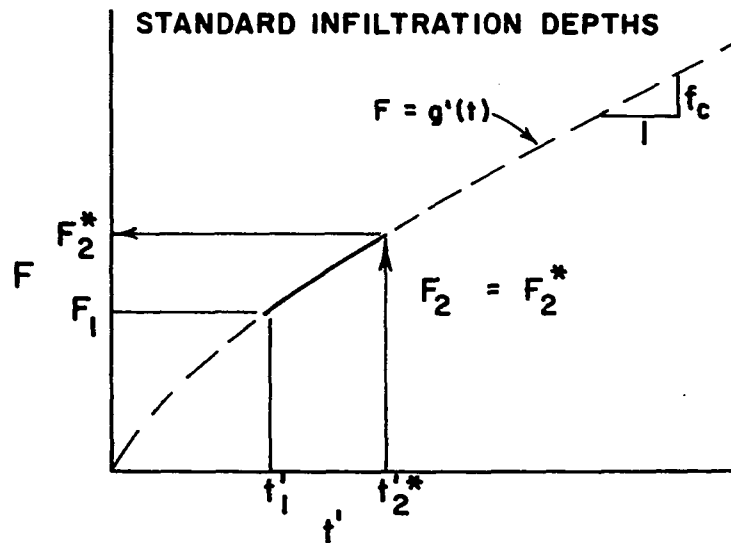
$$f = g(t) = f_c + (f_o - f_c)e^{-kt} \quad (13)$$

where symbols have the same meaning as in Equation 6.

2. Equation of mass infiltration,

$$F = g'(t) = f_c t + (f_o - f_c)(1/k)(1 - e^{-kt}) \quad (14)$$

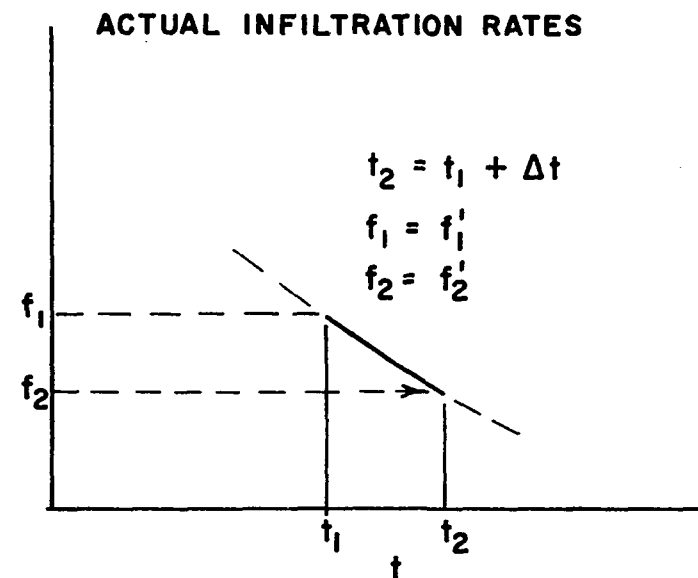
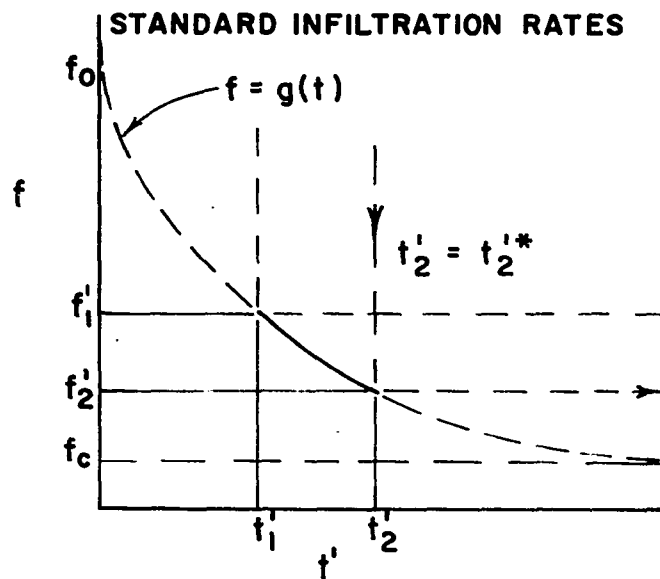
Figure 1. Rainfall excess analysis with rainfall excess



## RAINFALL EXCESS ANALYSIS

### RAINFALL EXCESS > 0

1.  $\Delta$  PRECIPITATION IN  $\Delta t$  TIME
2.  $t_2^* = t_1' + \Delta t$
3.  $F_2^* = g'(t_2^*)$
4.  $\Delta P > (F_2^* - F_1)$
5.  $\Delta RE = \Delta P - (F_2^* - F_1)$



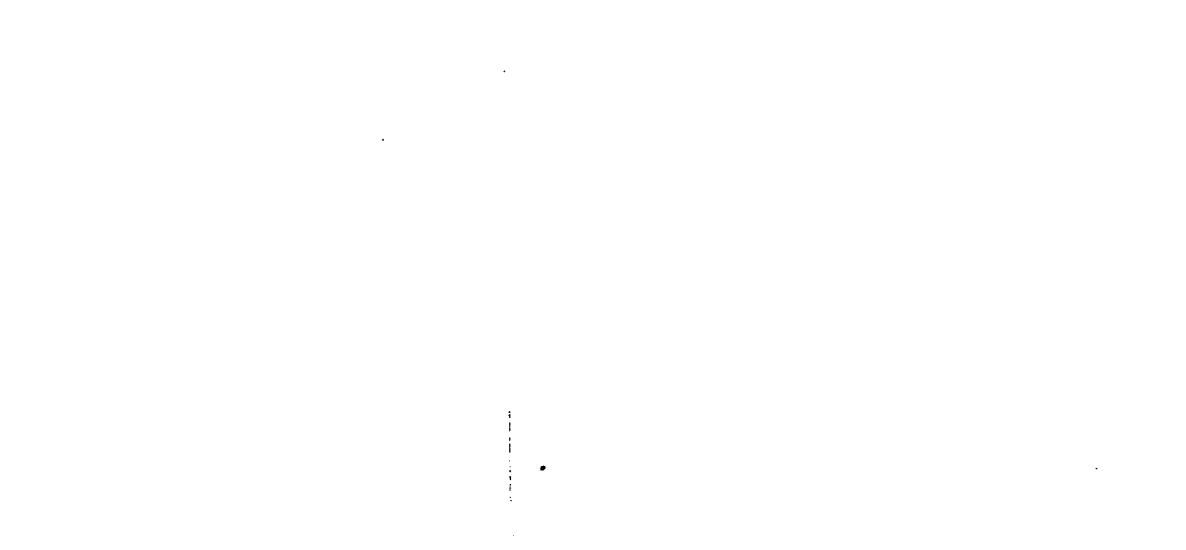
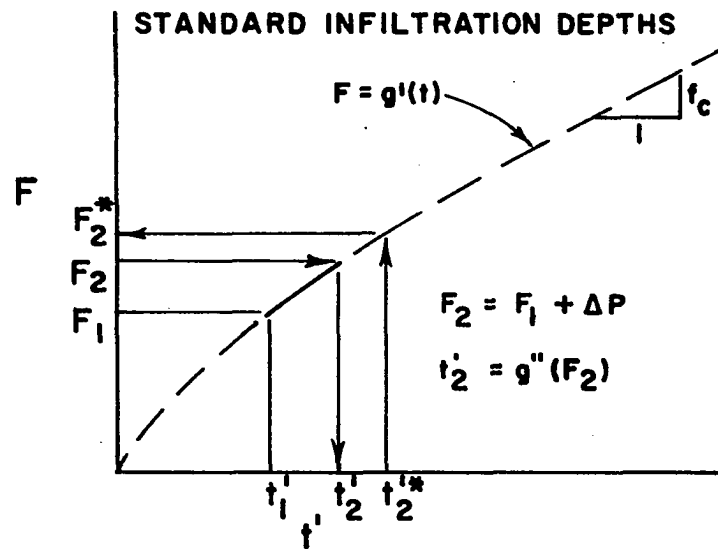


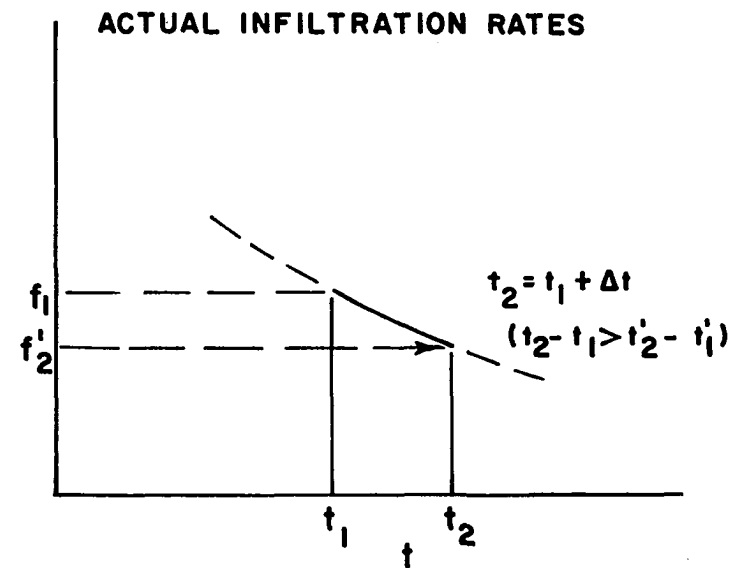
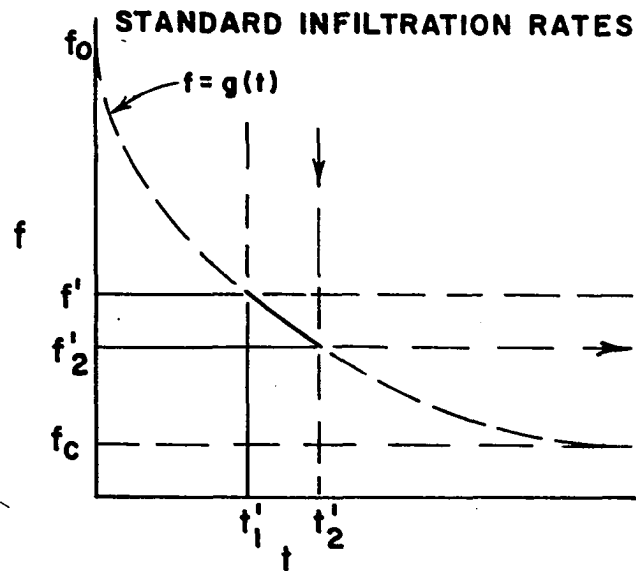
Figure 2. Rainfall excess analysis without rainfall excess



## RAINFALL EXCESS ANALYSIS

### RAINFALL EXCESS = 0

1.  $\Delta P$  PRECIPITATION IN  $\Delta t$  TIME
2.  $t_2^* = t_1 + \Delta t$
3.  $F_2^* = g'(t_2^*)$
4.  $\Delta P \leq (F_2^* - F_1)$
5.  $\Delta RE = 0$



and its inverse,

$$t = g''(F) \quad (15a)$$

Equation 14 is the integral of Equation 13. Equation 15a is solved in the form,

$$g''(t) = t - [(f_o - f_c)/(kf_c)]e^{-kt} - F/f_c + [(f_o - f_c)/(kf_c)] = 0 \quad (15b)$$

3. Time since beginning of storm,  $t_1$ .
4. Mass infiltration up to start of time increment under consideration,  $F_1$ .
5. Time computed from the equation of mass infiltration corresponding to the mass infiltration up to start of time increment under consideration,  $t'_1$ . Table 2 contains a listing of symbols and their meanings which will be used. In general, capital letters refer to accumulations, i.e., inches; and lower case letters refer to rates, i.e., inches per hour.

#### Procedure

1. Compute  $\Delta P$ , the depth of precipitation occurring in  $\Delta t$  time.
2. Compute  $t_2'^* = t_1' + \Delta t$ .
3. Solve  $F = g'(t)$  for  $F_2^*$ , letting  $t = t_2'^*$ .
4. Test to determine if  $\Delta P$  is  $>$  or  $\leq (F_2^* - F_1)$ . If  $>$ , proceed to step 5; if  $\leq$ , skip to step 6.
5. An increment of rainfall excess,  $\Delta RE$ , has accrued

Table 2. Symbols used for surface runoff computations

Symbol	Meaning
$T', P'$	accumulated time and precipitation, respectively, since beginning of storm from storm record
$\Delta T', \Delta P'$	increments of accumulated time and precipitation, respectively
$\Delta T, \Delta t$	five minutes
$\Delta P$	accumulated precipitation for a 5-minute increment
$\Delta T'/5$	number of 5-minute increments in $\Delta T'$
$T, P$	accumulated time and precipitation, respectively, from beginning of storm to beginning of time increment, $\Delta T$ , under consideration
$t, f$	abscissa and ordinate, respectively, of actual infiltration rate curve
$t', f'$	abscissa and ordinate, respectively, of standard (capacity) infiltration rate curve
*	a trial value of the dependent variable
$F, \Delta F$	total and increment, respectively, of accumulated infiltration depth
1, 2	subscripts denoting the beginning and ending, respectively, of the $\Delta t$ period under consideration



and is equal to  $[\Delta P - (F_2^* - F_1)]$ . See Figure 1.

- a.  $F_2 = F_2^*$ .
- b.  $t_2' = t_2'^*$ .
- c.  $t_2 = t_1 + \Delta t$ . This is the end of the procedure when there is rainfall excess.

6. No increment of rainfall excess,  $\Delta RE$ , has accrued.

See Figure 2.

- a.  $F_2 = F_1 + \Delta P$ .
- b. Solve  $t = g''(F)$  for  $t_2'$ , letting  $F = F_2$ .
- c.  $t_2 = t_1 + \Delta t$ . This is the end of the procedure when there is no rainfall excess.

The mass infiltration equation in the form of  $t = g''(F)$  requires an iterative solution. Newton's formula for approximation (11, p. 132) was used. Each newly computed value of  $t$  was compared with the value computed in the previous cycle. The iterative process was continued until the comparison produced a difference of less than 0.05 minutes.

The total volume of runoff accruing from each storm was obtained by summing the  $\Delta RE$  values for the entire storm, multiplying the sum by the watershed size in square miles to obtain the volume of runoff in square mile-inches. The volume-frequency analysis which follows in a later section utilized the summed  $\Delta RE$  values in inches.

## Prediction of Runoff Distribution

Knowledge of runoff depth alone is often of little value to the water control structure designer. He must also know the time-rate of generation of this runoff depth, or rainfall excess, and the time distribution of this runoff at the point of concern after it has been delayed by the runoff process. The unit hydrograph has proved to be a valuable tool by which the runoff distribution can be predicted.

### Unit graph derivation

Unit graph ordinates were obtained by the use of a modified form of Gray's method (13). However, the procedure used for the computation of runoff rates and volumes would have performed equally well if the unit graph ordinates had been obtained in any other manner. Consequently, ordinate values could have been obtained from an average distribution graph or by any synthetic method. If the ordinates were not computed by an initial portion of the computer program, a short storing routine could be used to insert the actual values into the desired memory locations.

General considerations      In order to apply the unit graph method to the prediction of storm hydrographs it is necessary that the time increments of the unit graph and the storm data be compatible. Storm data from U. S. Weather

Bureau records is customarily available in multiples of 5 minutes, whereas Gray's (13) time parameter for use in predicting unit graph ordinates is a function of  $P_R$ , the period of rise of the unit graph. At least three possibilities are available for reconciling this difference. First, use 5-minute increments for both. Second, use  $P_R/4$  for both as  $P_R/4$  is the time increment suggested by Gray for adequately defining the shape of the unit graph. Third, select some other suitable time parameter.

The idea of a critical duration for unit graph computations suggests one of the third possibilities, i.e., adopt a criterion for the selection of a critical unit duration and compute the resulting time increment for each watershed. In the actual adoption of such a criterion to a computer program it would be desirable to alter the resulting time increment slightly so that the increment was some multiple of 5 minutes. This would enable the summing of a predetermined number of storm increments and then treating the sum as a unit storm. One such criterion would be one-fourth of the period of rise of the watershed. For example, with a watershed having a period of rise of 42 minutes, 10 minutes could be used as the unit duration.

The first possibility, i.e., the use of 5-minute increments, was used in this study. It was selected because 1) 5 minutes is the commonly used format for presentation of

storm data, 2) the storm data would not have to be altered for application to different watersheds, and 3) it permitted certain simplifications in programming for the computer.

Modification of Gray's method (13) To use the 5-minute time increments for predicting storm hydrographs for any watershed, it was necessary to modify Gray's procedure (13) for the computation of unit graph ordinates. Gray's equation in the notation of this study is (13, p. 42)

$$Q_{t/P_R} = \frac{25.0(\gamma')^q}{\Gamma(q)} e^{-\gamma'(t/P_R)} (t/P_R)^{\gamma'} \quad (16)$$

where all symbols have the same meaning as in Equation 9.

The following changes are required:

1. Compute  $\Delta t/P_R$  where  $\Delta t$  is the desired time increment between computed ordinates. For this study,  $\Delta t = 5$  minutes.
2. Compute  $100(\Delta t/P_R)$ .
3. Replace 25.0 with  $100(\Delta t/P_R)$ .
4. Compute the ordinates of the dimensionless graph at desired points,  $t$ , with the revised equation. For example, if the midpoints of 5-minute increments are used, the first ordinate could be evaluated by the expression

$$Q_{2.5} = \frac{100(5/P_R)(\gamma')^q}{\Gamma(q)} e^{-\gamma'(2.5/P_R)} (2.5/P_R)^{\gamma'} \quad (17)$$

Due to the characteristics of the curve of the Gamma

distribution it is necessary to terminate arbitrarily the dimensionless graph ordinate computations. For this study the time of base of the unit graph is equivalent to 99.95% of the area under the curve of the Gamma distribution, i.e., the area under the unit graph represents at least 0.9995 inch of runoff instead of the usual one inch. The computer program could be easily modified to establish any desired percentage error.

Equation 17 computes the dimensionless graph ordinates with percentage units. Where actual rates of discharge in cubic feet per second are needed, the 100 in Equation 17 is divided so that the ordinate values are given as decimal fractions which are then multiplied by the appropriate constant. For  $t = 5$  minutes, the constant is 7744 A where A = area of watershed in square miles. The constant represents the area under the unit graph, i.e., a volume of one inch over the watershed area, as a function of  $t$ .

$$\frac{A \text{ sq.mi. (1 in.)}}{5 \text{ min.}} \times \frac{640 \text{ acre}}{\text{sq.mi.}} \times \frac{43,560 \text{ sq.ft.}}{\text{acre}} \times \frac{\text{min.}}{60 \text{ sec.}} \times \frac{\text{ft.}}{12 \text{ in.}}$$

$$= 7744 A \text{ cu.ft. per sec.}$$

#### The Spring Valley Creek Watershed unit graph

In order to use Gray's method (13) for unit graph derivation, the watershed must satisfy the basic assumptions of the derivation, such as location, size, and physiographic

limitations, and three parameters of the specific watershed must be known. The three parameters are watershed size, mean slope of the main stream, and length of the main stream. For the Spring Valley Creek Watershed these values were obtained as 7.65 square miles, 0.75%, and 5.54 miles, respectively. The unit graph ordinates are included in Appendix A.

#### Distribution prediction procedure

This section of the report describes the various steps of a procedure for predicting the time distribution of runoff from a small agricultural watershed. A section which follows will indicate how the steps were actually integrated to obtain a workable computer program. The method used to obtain 5-minute unit graph ordinates was introduced and referenced in preceding sections. The procedure used to obtain the time distribution of rainfall excess has also been outlined in an earlier section.

The time distribution of runoff from the Spring Valley Creek Watershed for each of the 996 excessive storms was obtained by the use of the standard unit graph procedure. For each unit of rainfall excess, the ordinates of an incremental runoff hydrograph were computed. An incremental hydrograph was defined as that hydrograph which results from multiplying an increment of rainfall excess times the unit graph ordinates. These incremental hydrograph (IH) ordinates

were then added to the summation of all previous IH hydrographs with due regard to time relations. That is, the newly computed IH was displaced timewise an amount equal to the time from the beginning of the storm~~2~~ to the beginning of the unit of rainfall excess, less one  $\Delta t$  increment. After all units of rainfall excess were processed in this manner the summation of all incremental hydrographs, the storm hydrograph (SH), was the predicted time distribution of runoff for that excessive storm.

Only the maximum or peak runoff rate was obtained from the predicted storm hydrograph and used in the ensuing analysis. However, a check was made on the volume of runoff by computing the area under the predicted storm hydrograph and, by application of the appropriate constants, obtaining the runoff volume in terms of inches of depth over the watershed.

### The Computer Program

#### Data processing sequence

A flow chart for the data processing is shown in Figure 3. The program is basically in two parts: 1) synthesis of the unit graph and 2) development of the storm hydrographs. Any desired method of hydrograph synthesis could be combined with the storm hydrograph development portion. The storm

**UNIT GRAPH  
(UG) SYNTHESIS**

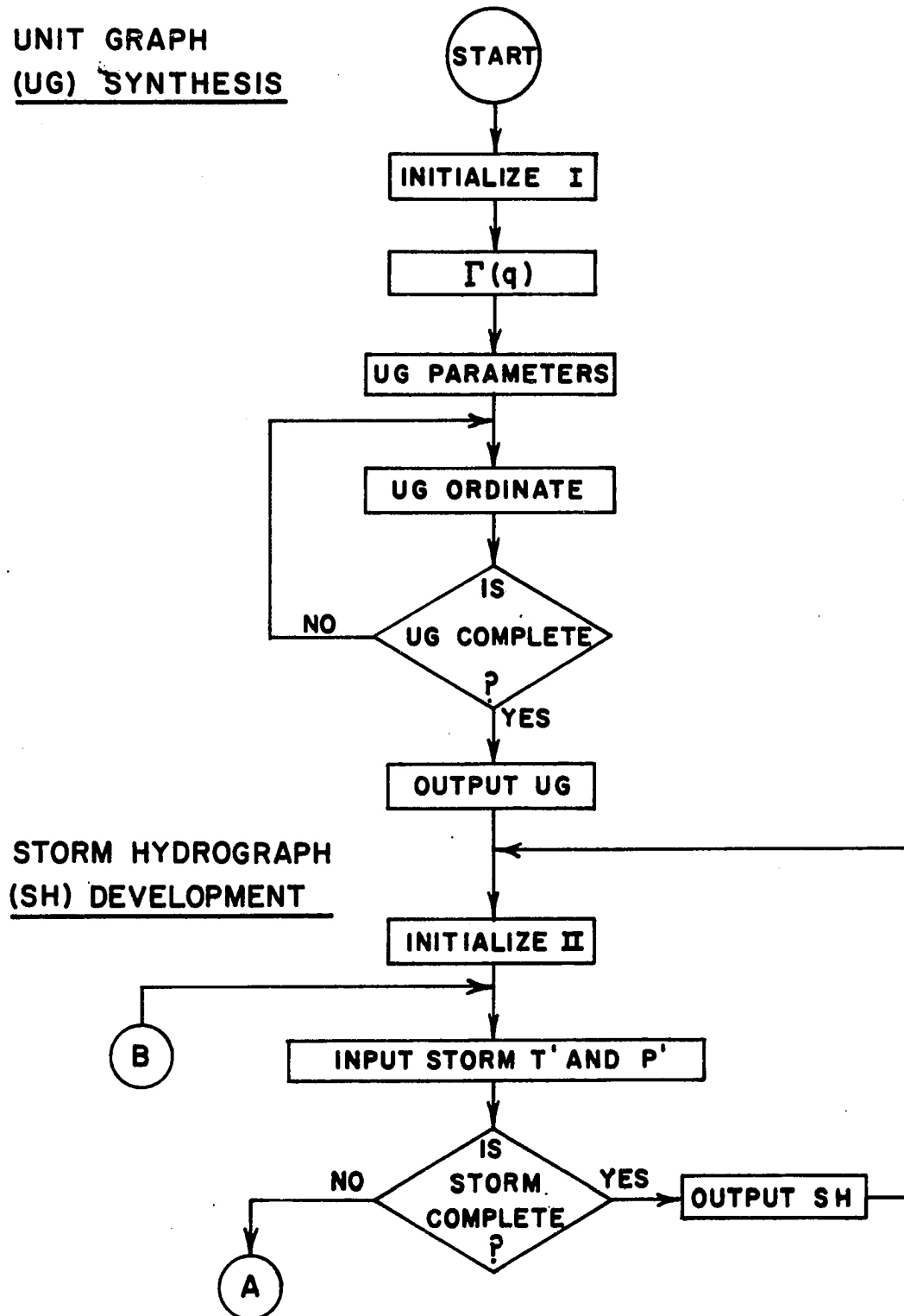


Figure 3. Computer flow chart



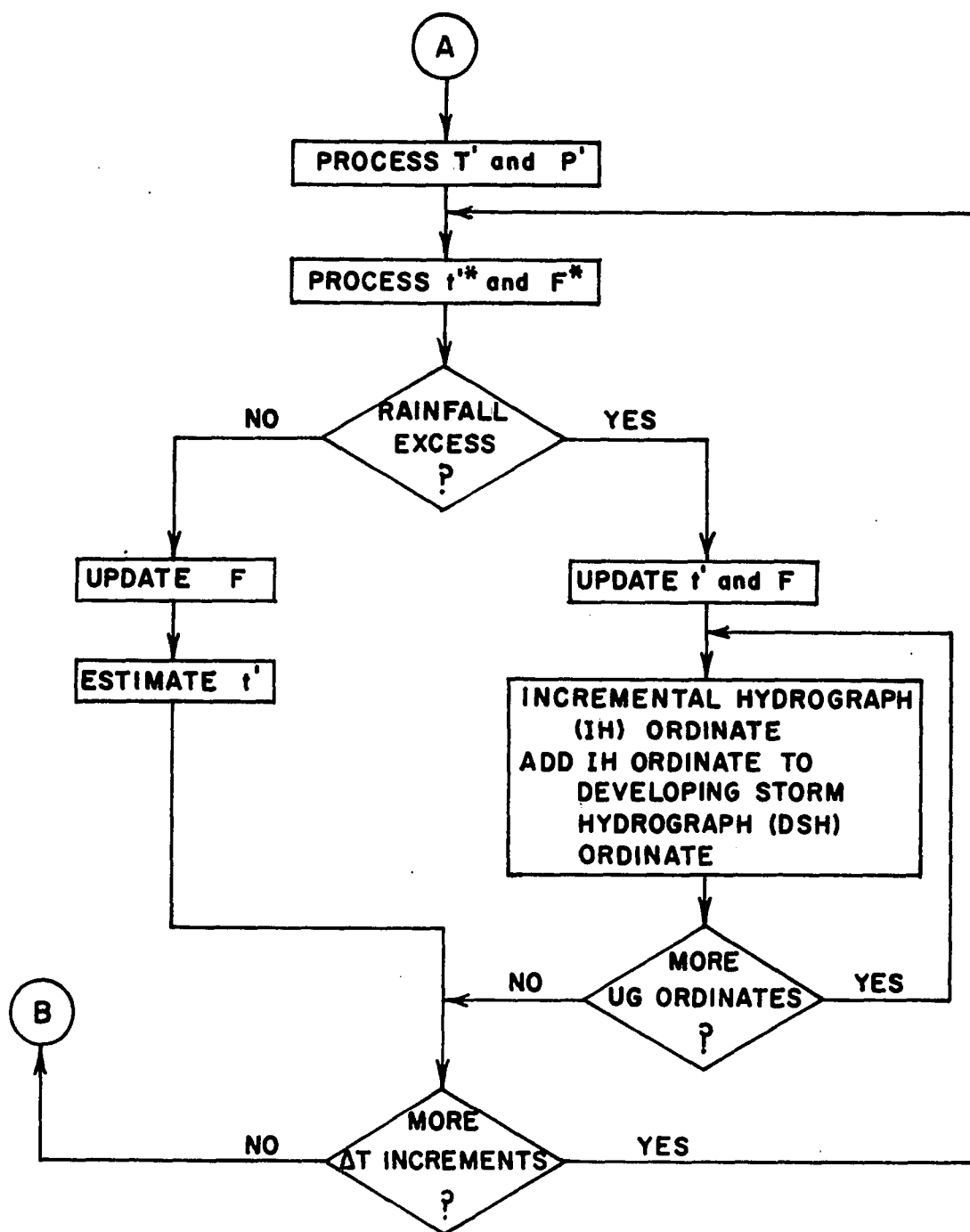


Figure 3. (Continued)

hydrograph development program is in no way restricted to use with the particular method of unit graph synthesis described herein. The unit graph could be input directly if it were available from analysis of actual runoff hydrographs.

As used herein the unit graph synthesis results in data amplification, i.e., a limited amount of input is processed to obtain a large amount of output. The storm hydrograph development is a data reduction process, i.e., large quantities of input are processed to obtain a limited amount of output.

The operations of the computer corresponding to each block in the flow chart of Figure 3 are described in Appendix A. The program order sequence is also included in Appendix A.

### Discussion

Certain aspects of the program posed somewhat unique problems.

1. At least two possibilities were available for obtaining values of Gamma ( $q$ ). The required value for any unit graph could be obtained either by programming the defining mathematical relationship or by storing a table of the Gamma function in the memory of the computer. Both methods were tried and the latter proved to be the better alternative even though an interpolation routine was required to obtain values intermediate to the table entries which were to the nearest

0.01. The method that was selected to program the defining mathematical relationship proved to be too costly in computer time to obtain the required degree of accuracy.

2. The unit graph program can be used to compute the unit graph ordinates for any watershed meeting the requirements of Gray's method (13) with only three changes in the input data. These are the three parameters required by the method to define the watershed, size and length and slope of the main stream.

3. The unit graph program can be altered quite simply to obtain ordinate values at the midpoints of any desired  $\Delta t$  increment.

4. As described earlier the procedure for obtaining increments of rainfall excess requires an iterative solution to the mass infiltration equation. The program is written in such a way that the degree of accuracy obtained in the answer can be easily altered by changing the constant which sets the maximum difference between successive values of the dependent variable. An increase in accuracy also means an increase in the computer time required.

5. Indexing was especially critical for the various operations required to obtain the storm hydrographs. Proper time relations had to be maintained between each of the incremental hydrographs and the developing storm hydrograph. This was further complicated by time periods in intermediate

positions during the storm period when the precipitation rate was less than the capacity infiltration rate. Special care was also required to insure that all indexes were properly initialized at the start of each new storm.

#### Processing sequence and computer time

The data were processed in two phases. In Phase 1 all 996 storms were used in predicting runoff peaks and volumes for an assumed watershed cover of all corn. Computing time for this phase was about six hours. For Phase 2 the 230 storms which gave the greatest runoff peaks with corn were used to predict runoff peaks and volumes for an assumed watershed cover of all legume-grass. Computing time for this phase was about two hours.

### Frequency Analysis of Peak Runoff Rates and Volumes

#### Presentation of results

The two predicted runoff quantities, peak runoff rates and volumes of runoff, were analyzed in a similar manner. The partial duration series was selected for the frequency analysis; predicted values of the runoff quantities were arranged in order of decreasing magnitude. The partial duration series were stopped at whatever magnitude of the variable gave the series a length equal to the number of

years of record included in the array. For example, 64 years of record were available from the Des Moines station; therefore, the corresponding partial duration series included the largest 64 values of the predicted runoff quantity. The source of the 16 series which were developed is shown in Table 3.

Table 3. Source of partial duration series

U. S. Weather Bureau stations	3	
Combined stations (all storms)	<u>1</u>	
Sub-total		4
Vegetative covers		2
Runoff quantities		2
Total = 2 x 2 x 4 = 16		

Figures 4 through 8 show the results of the frequency analysis. The magnitude of the runoff quantities was plotted as a function of its recurrence interval in years. It should be noted that these are semi-logarithmic plots with the arithmetic scale on the ordinate representing the runoff quantities and the logarithmic scale on the abscissa representing the recurrence intervals. Thus, portions of the curves which can be represented by straight line segments would have equations of the form,

$$Q = m \log T_r + b \quad (18)$$

where  $Q$  = runoff quantity,  $T_r$  = recurrence interval in years,  $m$  = slope of the curve, i.e., the numerical difference in ordinate values over one cycle of the logarithmic scale, and  $b$  = ordinate value at  $T_r = 1$ . An example of the calculations involved in the frequency analysis is given in Appendix B.

After considering the source and type of data represented by the frequency analysis, it was decided to fit the curves graphically. Ezekiel and Fox state that (9, p. 116)

. . . a curve fitted freehand by graphic methods, and conforming to logical limitations on its shape, may be even more valuable as a description of the facts of the relationship than a definite equation and corresponding curve selected empirically, but fitting less well.

Benson writes that (3, p. 11)

In the graphical method, frequency curves are drawn by eye to average the plotted points. Straight lines are not drawn, regardless of the type of plotting paper used, unless so indicated by the data. There is always the possibility that the highest flood or floods within a short period of record may have a larger or smaller recurrence interval than actually computed. For this reason the curve is not drawn through or near the highest flood unless it follows the trend of the lower points.

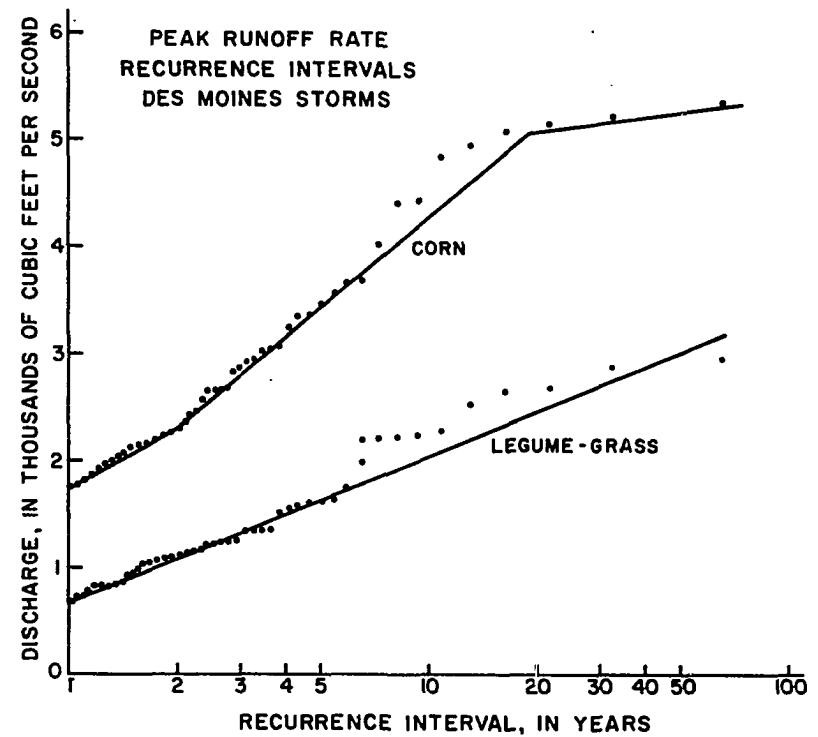
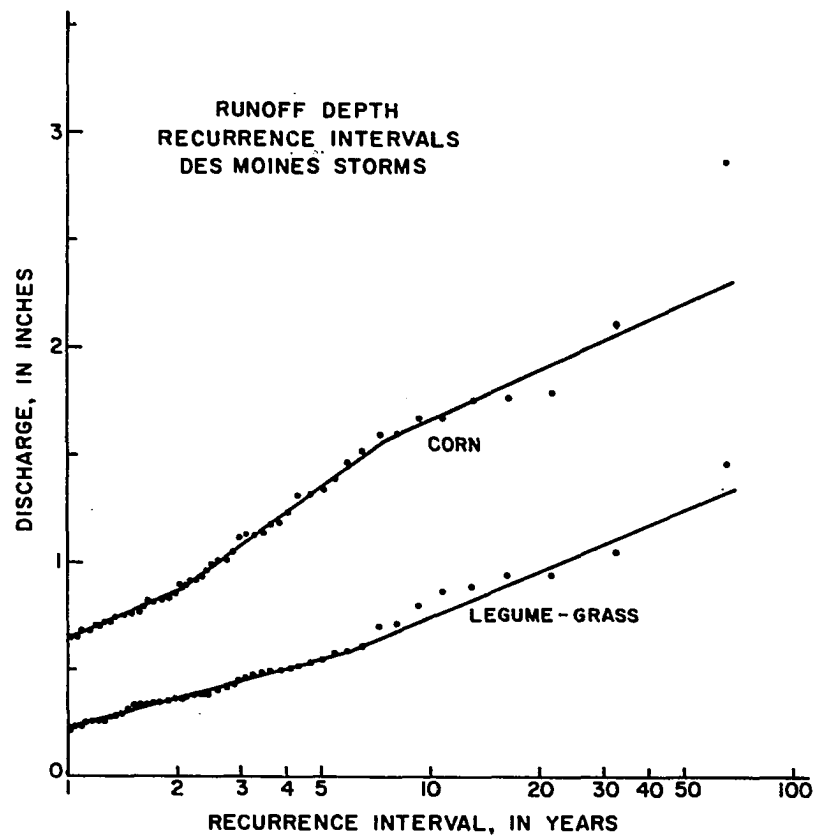


Figure 4. Runoff recurrence intervals, Des Moines storms,  
Spring Valley Creek Watershed

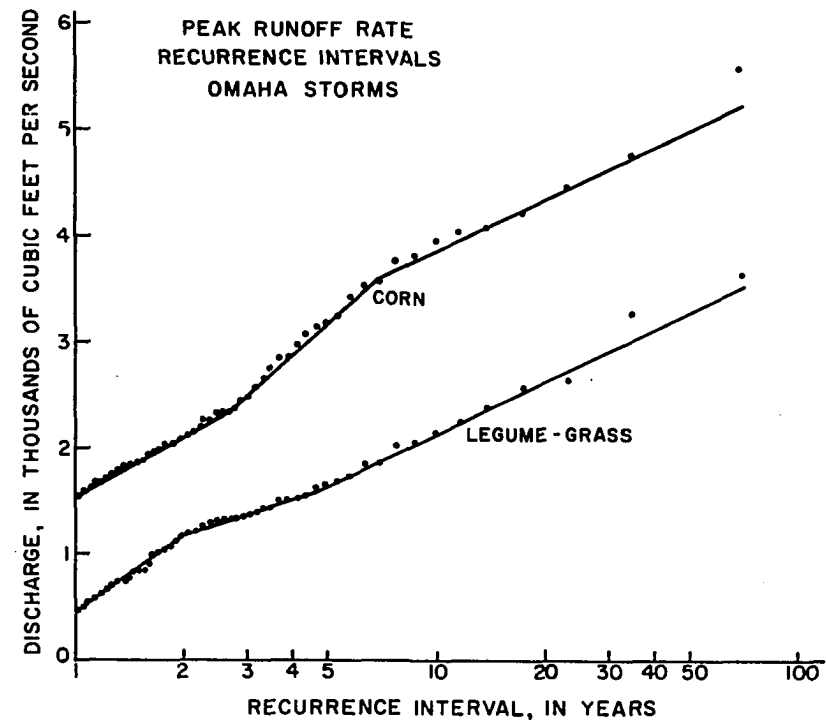
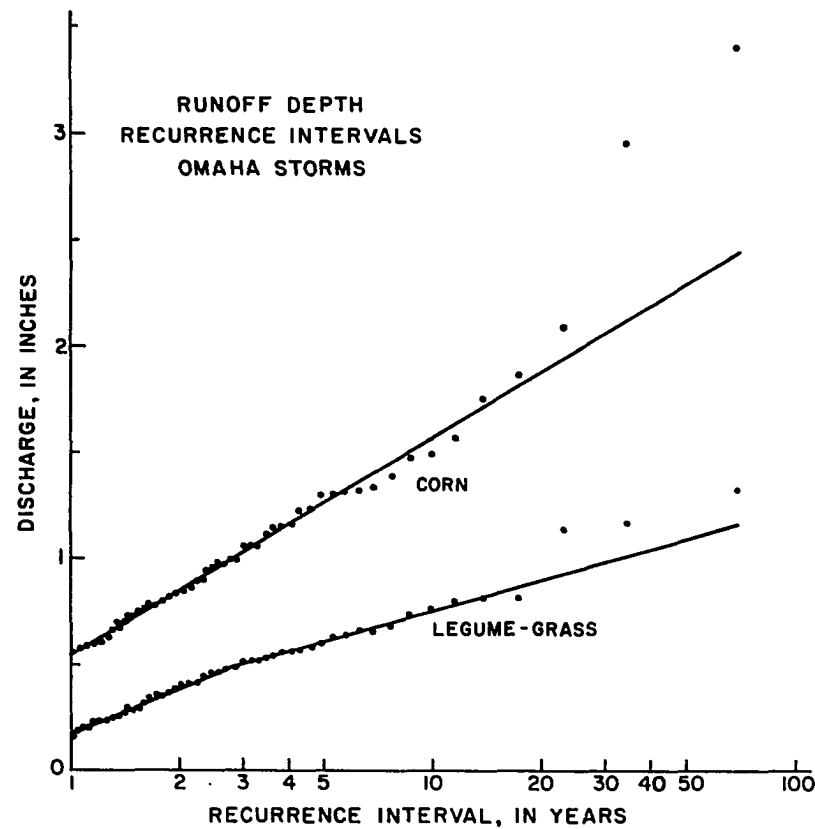


Figure 5. Runoff recurrence intervals, Omaha storms,  
Spring Valley Creek Watershed



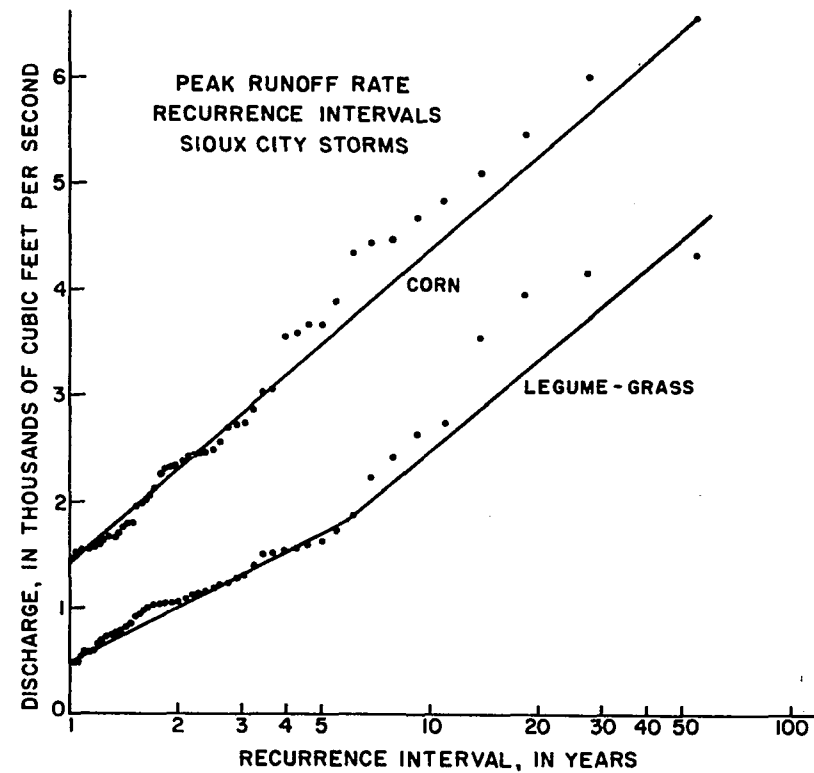
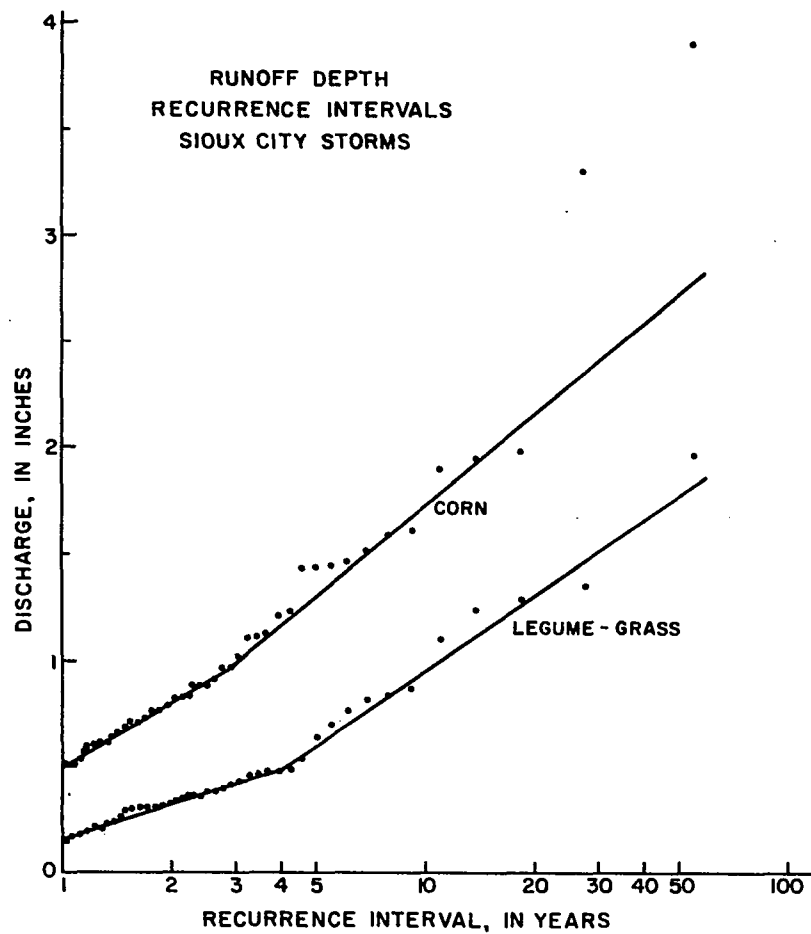


Figure 6. Runoff recurrence intervals, Sioux City storms,  
Spring Valley Creek Watershed

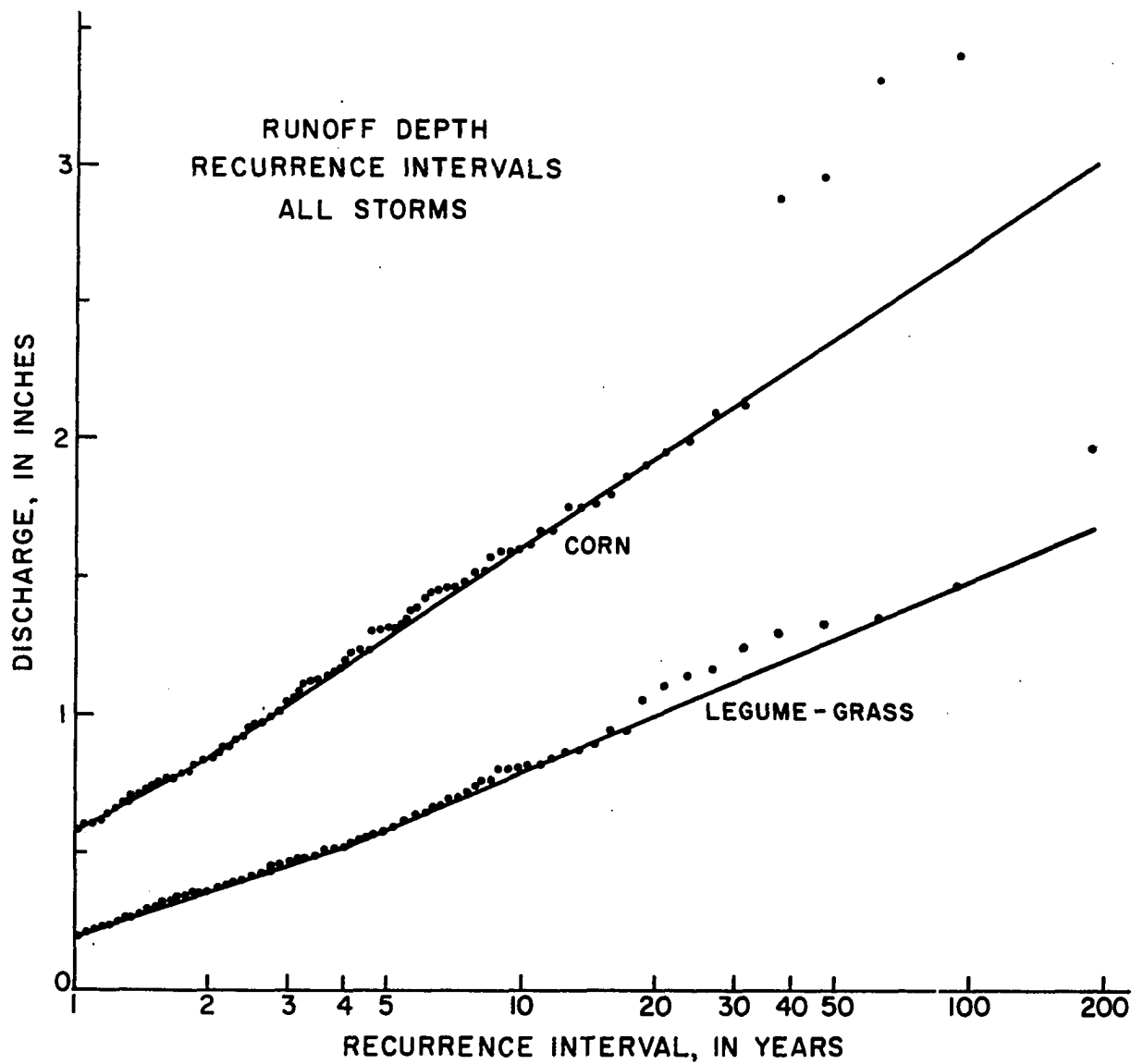


Figure 7. Runoff depth recurrence intervals

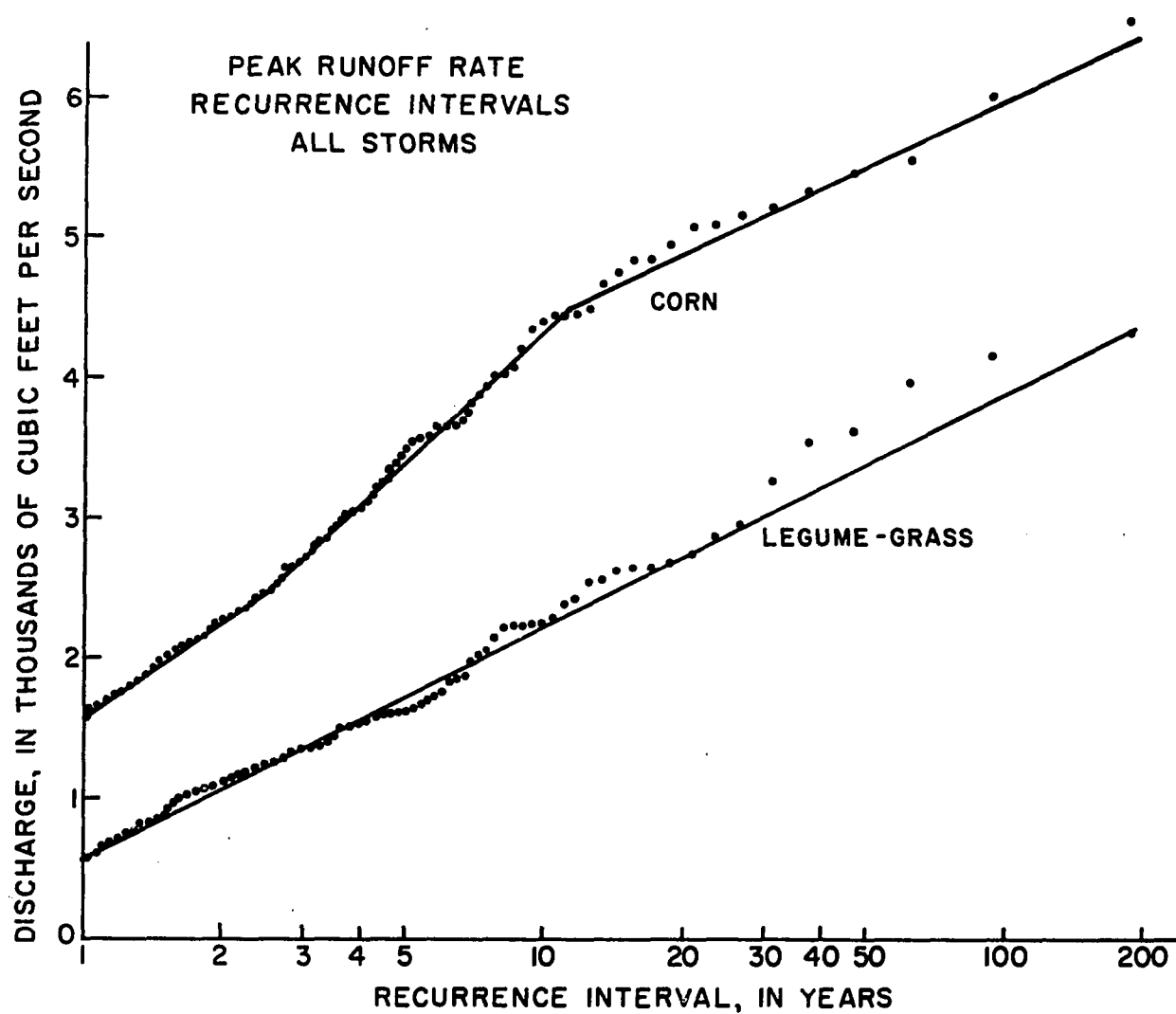


Figure 8. Peak runoff rate recurrence intervals,  
Spring Valley Creek Watershed

## Discussion of results

Several statements can be made based on the results of the frequency analysis for Spring Valley Creek Watershed.

1. In general, semi-logarithmic plots exhibit a continuous functional relationship between the two runoff quantities, peak rate and depth, and recurrence interval.

The five largest runoff depth values for corn exhibit the greatest deviation from the semi-logarithmic curves. Total precipitation of the storms causing the five largest values was greater than for the next five. All the storms which gave the five largest runoff depth values had total precipitation depths greater than 4.23 inches; whereas the next five had depths of less than 3.74 inches. This, however, does not explain the deviation since the same storms when used with legume-grass cover gave runoff depth values which, in general, fit the semi-logarithmic plot.

2. The procedures and frequency analysis described above provide a procedure whereby the designer of water control facilities can base his designs on a recurrence interval attached to the pertinent runoff quantity instead of the recurrence interval of the rainfall. When the recurrence interval is associated with the rainfall, it is necessary to assume a magnitude for all losses including infiltration. When the recurrence interval is associated with the runoff, the magnitude of the infiltration loss need not be separately

assumed. Since infiltration rates were computed as a function of the 7-day API, the antecedent moisture conditions at the time of each runoff-producing storm as well as cover have been considered. As pointed out later in this report, much additional study is needed toward quantitatively predicting infiltration rates.

3. The difference between ordinates for corn and legume-grass for any specified recurrence interval roughly represents the maximum range of runoff possibilities that could be credited to watershed cover. The runoff quantities to be expected for a specified recurrence interval for a combination of the two covers can also be predicted. The extreme values of the runoff quantity can be obtained from the frequency analysis curves and then these values can be weighted according to the relative proportions of the watershed area credited to each cover.

4. There is a tendency for the recurrence interval curves to diverge at larger recurrence intervals. As an example, for Figure 7 the 10-year recurrence interval is 1.61 inches for corn and 0.78 inch for legume-grass, a difference of 0.83 inch. At 50 years the corresponding values are 2.37 inches for corn and 1.27 inches for legume-grass, a difference of 1.10 inches. Thus, the absolute reduction in depth of runoff due to cover increases with an increase in recurrence interval. This tendency is quite pronounced for

all of the runoff depth curves. It also exists for the lower recurrence intervals for the peak runoff rate curves.

The percentage reductions in expected depths of runoff due to cover for the numerical example used in the preceding paragraph are 51.5% and 46.4% for the 10-year and 50-year recurrence intervals, respectively. Similar computations for peak runoff rates give absolute reductions of 2080 and 2140 cubic feet per second for the 10- and 50-year recurrence intervals, respectively. The corresponding percentage reductions due to a change in cover from corn to legume-grass are 48.2% and 38.8%. Even a moderate reliance on the reliability of the infiltration estimates used in the study would require one to conclude that vegetative cover can make very significant differences in expected runoff depths and peak runoff rates.

5. Variation in the rank of the storms with regard to the different runoff quantities is shown in Table 4. The storms are nominally arranged according to the depth of runoff from corn for the 15 largest amounts. The four additional storms are included so that the 15 largest values of depth of runoff from legume-grass are also used in the ranking. In general, a storm which would be critical for design for one runoff quantity and one cover would not be the critical storm for the other runoff quantity and/or cover. As an example, storm "a" (Table 4) produced the largest depth

Table 4. Variation in rank of storms

Storm	Precipitation	Corn runoff		Legume-grass runoff	
		Depth	Rate	Depth	Rate
a	1	1	12	6	38
b	2	2	13	4	13
c	5	3	1	1	3
d	3	4	30	-*	-
e	6	5	7	2	18
f	15	6	5	15	23
g	20	7	3	8	6
h	17	8	4	14	9
i	10	9	20	-*	-
j	32	10	2	5	2
k	18	11	22	-*	-
l	16	12	24	10	11
m	8	13	6	13	10
n	12	14	9	12	7
o	36	15	21	-*	-
p	73			3**	1
q	76			7**	4
r	77			9**	5
s	7			11**	8

\*Not included in list of 15 storms which produced the largest runoff depths from legume-grass cover.

\*\*Not included in list of 15 storms which produced the largest runoff depths from corn cover.

of runoff from corn, the 12th largest peak runoff rate from corn, the 6th largest runoff depth from legume-grass, and the 38th largest peak runoff rate from legume-grass.

This variation in rank raises a question as to the validity of the practice of specifying design storms by using a standardized intensity sequence. Runoff quantities are, in fact, the result of interactions among the various storm parameters, i.e., intensity, intensity sequence, and duration, and the time-rates of infiltration and the other "losses".

#### Comparison of results

A comparison was made between the 50-year recurrence interval runoff quantities predicted by this study and the corresponding values predicted by the method currently used by the U. S. Soil Conservation Service in Iowa (53, 54). The SCS method is used for the design of full flow structures on drainage areas larger than 600 acres. Values were developed for runoff volumes and peak runoff rates.

#### Runoff volumes:

50-year, 6-hour rainfall = 4.75 inches

Curve number for corn (row crops, straight row, fair condition, antecedent condition II) = 80

Curve number for legume-grass (pasture, fair condition, antecedent condition II) = 69

Runoff volume for corn = 2.68 inches

Runoff volume for legume-grass = 1.78 inches



## Peak runoff rates:

Hydrograph family for corn--2.50

Hydrograph family for legume-grass--3.25

Time of concentration = 1.35 hours (= length of main stream, 29,251 feet, divided by an assumed average velocity of flow of 6 feet per second)

Peak runoff rate for corn = 5536 cubic feet per second (= 270 cubic feet per second per square mile per inch of runoff x 7.65 square miles x 2.68 inches)

Peak runoff rate for legume-grass = 3336 cubic feet per second (= 245 cubic feet per second per square mile per inch of runoff x 7.65 square miles x 1.78 inches)

A comparison of the results of the two methods is shown in Table 5. Considering the nature of the quantities that have been predicted and the assumptions that had to be made for both methods, results of the two methods compare quite closely.

Table 5. Comparison of results with SCS method

Quantity	SCS method	Present study
Runoff volumes		
Corn, inches	2.68	2.37
Legume-grass, inches	1.78	1.27
Peak runoff rates		
Corn, cubic feet per second	5536	5500
Legume-grass, cubic feet per second	3336	3380

Another independent estimate of the 50-year recurrence interval peak runoff rate was made according to a method that was proposed by the U. S. Bureau of Public Roads (44). The method is based on indexes of watershed area, precipitation, topography, and drainage density. For the Spring Valley Creek Watershed the method predicts 5300 cubic feet per second.

It should be kept in mind that the procedure that has been described for predicting runoff rates and volumes applies only to the surface component. Neither base flow nor transmission losses are included. For the major portion of applications there would be no base flow; however, where it did exist the designer would need to make an independent estimate of its magnitude and add the result to the surface runoff prediction obtained by the procedure described in this report. Estimates of transmission losses would need to be subtracted.

## SUMMARY AND CONCLUSIONS

Storm hydrographs from records of individual storms can be predicted within the limits of the accuracy of infiltration theory and the unit hydrograph principle. This study has developed and used procedures for solving a surface runoff equation of the form,

$$\text{Runoff} = \text{Rainfall} - \text{Infiltration losses}$$

Rainfall data were obtained from recording raingage charts for 996 "excessive" storms of record from the U. S. Weather Bureau stations at Des Moines and Sioux City, Iowa and Omaha, Nebraska. With cover as an independent variable, an index of rainfall deficiency, the 7-day antecedent precipitation index, for each of the storms was used as the parameter for predicting the constants for infiltration rate and depth equations. Rainfall excess amounts were then computed for 5-minute time increments throughout the entire length of each of the storms.

The rainfall excess amounts were routed by use of a synthetic watershed unit hydrograph to obtain two significant quantities, the peak runoff rate and the runoff volume, of the runoff hydrograph. The unit hydrograph was synthesized using a procedure which is based on the Gamma distribution.

Application of the procedures described above to the

Spring Valley Creek Watershed in southwestern Iowa provided recurrence interval data for both peak rates and volumes of runoff.

The high speed operation of the electronic digital computer made possible the practical application of the procedures described above. A major task of the study was writing the computer program for applying the procedures. The program that was developed is quite flexible in application in that quantitative runoff predictions can be quite easily made from a large variety of assumptions as to rainfall amount and distribution, infiltration losses, and source and shape of the unit hydrograph.

## RESEARCH NEEDS

Even though the present study was primarily concerned with developing a procedure for solving the general surface runoff equation based on the infiltration theory of runoff and the unit hydrograph principle, as the study progressed it became quite evident that numerical predictions could have been improved if certain additional information would have been available. Specifically, the need for additional research was noted in two areas: one, infiltration estimates and two, losses during overland and channel flow.

Sound infiltration estimates are of considerable importance in obtaining runoff estimates from small agricultural watersheds. This importance is derived from the interactions among effects of storm variations, cover, soil, moisture, and temperature. The manner in which storm variations were handled in the present study perhaps approaches the ideal. Further study could discern the storm variations which are critical for the various combinations of the other variables affecting infiltration. Cover effects include variations from differences in the actual plant species, in the stage of maturity and vigor of growth, and in the management the cover has received. The effects on infiltration of variations in the soil, antecedent moisture, and temperature are still poorly understood for engineering applications.

It is generally recognized that losses during overland and channel flow do occur. Little quantitative information is available. There appears to be no logical reason why the same phenomenon may not generally occur through reaches of the drainage systems of small agricultural watersheds. In fact, one recent study (1) adopted this explanation for the difference between measured and predicted runoff volume. Additional study of the variables and the magnitude of such losses is needed.

In addition to the two research needs cited above, continued collection and interpretation of rainfall data should be made to improve the relationships that now exist between point rainfall and the distribution of this recorded rainfall over the surrounding area.

A major objective of hydrologic research is the prediction of the outflow hydrograph over extended periods of time. Any research directed toward this objective is worthy of serious consideration.

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## ACKNOWLEDGMENTS

Acknowledgment is hereby made to:

Professors Hobart Beresford and Merlin G. Spangler for their interested participation in the planning and prosecution of my graduate program and to Professor Spangler for serving as co-chairman of the committee in charge.

Dr. Howard P. Johnson for his constructive suggestions and criticism throughout the development of the problem and the writing of the dissertation and for serving as co-chairman of the committee in charge.

Dr. John F. Timmons for insights into the application of economics to problems of soil and water conservation.

Dr. E. Robert Baumann for communicating to me his awareness of the challenges of hydrologic problems.

Robert A. Sharpe of the CYCLONE Computer Laboratory for his suggestions on programming.

The several people who have processed raingage charts over the last eight years.

My family--and especially my wife, Beverly--for their help along the way.

## APPENDIX A

## Flow Chart Description

The operations of the computer corresponding to each block in the flow chart of Figure 3 are as follows:

Start

The CYCLONE computer with the interpretive program, EERIE, was used for the data processing. Typically the computer performs in sequence two separate operations: 1) the orders are stored sequentially as they will later be used and 2) input data are then presented for processing by the previously stored program. The storing of the program is initiated by a "black switch start" on the computer console.

Initialize I

The number 600 is placed in index register (IR) 5 as the maximum number of unit graph (UG) ordinates which is permitted. IR 5 is then used to control the storing and retrieval of UG ordinates. A table of the Gamma function values is stored for later use in UG synthesis. Constants for the UG synthesis equations are stored as are certain other conversion and testing constants. The watershed parameters are loaded, i.e., watershed size and length and

slope of the main stream. Titles for the computations are input and output. These program constants and watershed parameters are included later in this appendix. Parameters required for UG synthesis are computed. They are  $P_R$ ,  $\gamma'$ ,  $q$ , and  $(\gamma')^q$ .

### $\Gamma(q)$

The table of the Gamma function gives  $\Gamma(n)$  for values of  $n$  from 1.00 to 2.00 inclusive. The values of  $q$  computed in "Initialize I" are greater than 2.00 and have more than three significant digits. Therefore,  $\Gamma(q)$  is obtained from the equation,  $\Gamma(q) = x \Gamma(n)$  where  $1.00 \leq n \leq 2.00$ . Values of  $x$  and  $n$  are first obtained and then  $\Gamma(n)$  is obtained by a straight line interpolation routine in the stored Gamma table.

### UG parameters

Certain constants are computed for use in synthesis of the UG. The area under the UG is represented by 7744 A, where A is the size of the watershed in square miles, i.e., a volume of one inch over the watershed area, as a function of  $\Delta t$ .  $\Delta t$  was used as 5 minutes. To obtain runoff rate in cubic feet per second, 7744 A is used. Another parameter is

$$(\Delta t/P_R) (\gamma')^q / \Gamma(q)$$

which is the portion of Equation 17 which remains constant for all UG ordinates.  $\Delta t/2$  gives the abscissa for the first UG ordinate, i.e., 2.5 minutes.

#### UG ordinate

UG ordinates are computed as a decimal fraction and then multiplied by 7744 A to obtain cubic feet per second. These values are then stored in sequence for later use in development of the storm hydrographs. They were also printed and are included later. IR 13 was incremented by one after each ordinate was computed so that the total number of ordinates would be available for later use.

#### Is UG complete?

As each ordinate in decimal fraction form is computed, it is added to the sum of all previously computed ordinates. The theoretical sum of these values for the entire UG is one. In order to limit the total number of ordinate values, 0.9995 was used to test for completion of the UG synthesis computations. If the UG is not complete, program execution returns to the "UG ordinate" block; otherwise control is transferred to the "Output UG" sequence.

Output UG

In addition to storing and printing UG ordinates as they are computed, UG abscissas are also printed. After all ordinates have been computed the peak is defined by computing and printing the period of rise,  $P_R$ , and the maximum discharge of the UG. A summation of the UG ordinates was also obtained and printed.

Initialize II

Constants for the infiltration parameter prediction equations as well as additional conversion and testing constants are stored. Program execution is routinely halted at this stage for insertion of a storm data tape. Execution is re-started with a "black switch start". In actual operation more than one storm is usually included on a specific piece of paper tape. An "ignore" switch on the console is set to reject this halt so that the computation of storm hydrographs is a continuous operation. As the end of a particular piece of storm data tape approaches the reader, the "ignore" switch is re-set to cause the computer to obey the halt order.

Index registers 4, 10, 11, and 12 are loaded with 5, 1000, 1000, and 600 respectively. IR 4 controls the loading of the five storm identification numbers. IR 10 controls the time on the developing storm hydrograph (DSH) at which



storage of the incremental hydrograph (IH) is started. IR 11 controls storing of the DSH. IR 12 controls the locating of the UG ordinates.

The five storm identification numbers are loaded and printed. They are geographical location code, month, day of month, year, and 7-day antecedent precipitation index (API). Then the parameters of the infiltration equations are computed. The parameter prediction equations, which have API as the independent variable, predict for each storm values of  $f_c$ ,  $f_o$ ,  $k$ ,  $(f_o - f_c)$ , and  $(f_o - f_c)/kf_c$ .

#### Input storm T' and P'

From the storm data tape input the next value of accumulated time since the beginning of the storm.

#### Is storm complete?

This decision is based on the sign of the new T' value. This is possible since a minus one was placed at the end of each set of storm data. If the storm is complete, program execution goes ahead to the "Output SH" block; otherwise control is transferred to the "Process T' and P'" sequence.

#### Process T' and P'

Values are computed for  $\Delta T'$ ,  $\Delta T'/5$  which is the number of  $\Delta t$  ( $= \Delta T = 5$ ) increments,  $\Delta P'$ , and  $\Delta P$  which is the

accumulated precipitation for each  $\Delta t$  increment of  $\Delta T'$ .  $\Delta T'/5$  is loaded into IR 6 for later use in determining if there are more  $\Delta T$  increments to be processed.

#### Process $t'^*$ and $F^*$

$T$  and  $P$  are updated. They are accumulated time and precipitation, respectively, from the beginning of the storm to the beginning of the time increment,  $\Delta T$  ( $= \Delta t$ ), under consideration. A new value of  $t'$  ( $= t'^*$ ) is assumed to be equal to  $t' + 5$ . The corresponding value of  $F^*$  is computed from the mass infiltration relation, that is,

$$F = g'(t)$$

$$F^* = g'(t'^*)$$

This relationship is graphically represented on the standard infiltration depth curves of Figures 1 and 2.

#### Rainfall excess?

The difference,  $(F^* - F)$ , represents the maximum depth of infiltration that could occur during the  $\Delta t$  ( $= 5$ ) increment. The test to determine if rainfall excess has occurred during the  $\Delta t$  increment is made by comparing the difference,  $(F^* - F)$ , with  $\Delta P$ , i.e., was there sufficient rainfall during the time increment to satisfy the capacity infiltration requirements represented by the standard infiltration curves?

If there was not sufficient rainfall, program execution proceeds to the "Update F" sequence; otherwise control is transferred to "Update t' and F".

#### Update F

F is the accumulated infiltration depth. When there is insufficient precipitation to produce rainfall excess, F is updated by computing the sum  $(F + \Delta P)$ , i.e., the entire  $\Delta P$  increment is infiltrated.

#### Estimate t'

t' is estimated iteratively by successive solutions of the inverse of

$$F = g'(t),$$

i.e., by solving

$$t' = g''(F).$$

The old t' value is used as the first approximation of the new t'. The number of decimal places of accuracy doubles with each successive approximation. A constant of 0.05 minutes was used to test the adequacy of each approximation. When the absolute value of the difference between a particular t' approximation and the immediately preceding t' approximation became less than 0.05 minutes, the iterative cycling was

stopped and control was transferred to "More  $\Delta T$  increments?".

#### Update $t'$ and $F$

If there is rainfall excess, the new  $t'$  is equal to the old  $t'$  plus 5 minutes, i.e., movement along the abscissa scale is the same for both standard and actual infiltration curves. The new value of  $F$  is equal to  $F^*$  which was computed in the "Process  $t'^*$  and  $F^*$ " sequence, i.e., infiltration is assumed to occur at the capacity rate throughout the  $\Delta t$  increment.

#### Incremental hydrograph (IH) ordinate

The IH is obtained by successively multiplying the UG ordinates by the increment of rainfall excess. IR 12 is used to locate the UG ordinates in sequence.

#### Add IH ordinate to developing storm hydrograph (DSH) ordinate

As each ordinate of the IH is computed, it is added to the proper DSH ordinate. By "proper" is meant the IH is correctly positioned with respect to the time scale of the DSH.

#### More UG ordinates?

After each ordinate of the IH is computed, IR 13 is checked to see if all UG ordinates have been used. This

is accomplished by initially placing the number of UG ordinates in IR 13 and then decrementing IR 13 by one after each UG ordinate is used in producing the IH. IR 12 and IR 11 are also decremented by one so the next UG ordinate is used and the resulting IH value is added "properly" to the DSH. If all UG ordinates have not been used, control is returned to the "Incremental hydrograph (IH) ordinate" sequence; otherwise proceed to "More  $\Delta T$  increments?".

More  $\Delta T$  increments?

IR 12 is reloaded with 600 to control the locating of UG ordinates for the next rainfall excess increment; IR 13 is reloaded with the number of UG ordinates. IR 10 is decremented by one and the same number is placed in IR 11 to control the start time on the DSH for the next IH. IR 14 is incremented by one to count the number of  $\Delta t'$  increments in the DSH.

IR 6 is used to determine if there are more  $\Delta t$  increments. The number of such increments in  $\Delta T'$  was stored therein and this number is decremented by one as each is used. If there are more, control is transferred to the "Process  $t'*$  and  $F^*$ " sequence; otherwise program execution returns to "Input storm  $T'$  and  $P'$ ".

Output SH

When the storm is complete, i.e., when all T' and P' values have been processed, control is transferred to the output routine. The maximum SH value is determined and printed. Other values which are output are the volume of runoff in square mile-inches, the depth of runoff, and the depth of rainfall.

Program

begin	205;	
lxd	*,5,600;	
lxd	*,7,101;	
inp	201,7;	
tix	*-1,7,1;	Gamma (n) Table
halt	*+1;	Insert tape with constants
lxd	*,6,13;	
inp	94,6;	13 constants
tix	*-1,6,1;	
inp	95;	
inp	96;	
inp	97;	
ainp	1900;	Title of computations
crlf	1;	
aout	1900;	
crlf	1;	
out	95,,032;	A
out	96,,032;	L
out	97,,033;	S sub c
ainp	1940;	
crlf	1;	
aout	1940;	Column headings
sqrt	97;	
sto	80;	Square root of S sub c
idiv	96;	
log	;	
mul	82;	
exp	;	
mul	81;	
sto	79;	
mul	84;	
sto	78;	
cla	85;	
sub	78;	
sto	77;	
cla	83;	
mul	79;	
div	77;	
sto	76;	P sub R
div	79;	
sto	75;	Gamma
add	85;	
sto	63;	q
log	75;	
mul	63;	
exp	;	
sto	74;	

cla	85;	
sto	65;	x
cla	63;	
sub	92;	
trn	*+11;	
add	92;	
sub	85;	
sto	66;	
mul	65;	
sto	65;	
cla	66;	
sub	92;	
trn	*+3;	
add	92;	
tru	*-8;	$\Gamma(q) = x \Gamma(n)$
add	92;	
sto	64;	n
cls	64;	$-n = -1.486$
mul	89;	$-100n = -148.6$
sto	42;	
add	85;	$-147.6$
lxn	,8;	$4096-148 = 3948$
sxn	41,8;	3948
cls	42;	148.6
add	41;	$148.6 + 3948 = 4096.6$
sub	88;	$4096.6 - 4096 = 0.6$
sto	41;	$k = 0.6$
cla	,8;	$0-3948 = 4096-3948 = \text{location } 148$
sto	43;	$\Gamma \text{ of } 1.48$
txi	*+1,8,4095;	3947
cla	,8;	$4096-3947 = \text{location } 149$
sub	43;	$\Gamma \text{ of } 1.49 - \Gamma \text{ of } 1.48$
mul	41;	$k \Delta \Gamma$
add	43;	$\Gamma n$
mul	65;	
sto	62;	$\Gamma q$
cla	87;	
mul	95;	
sto	73;	7744 A
stz	67;	
stz	60;	Initial value of $\Sigma Q$
cla	91;	
div	76;	
sto	61;	5/P sub R
mul	74;	
div	62;	
sto	72;	
cla	90;	
mul	91;	



div	76;	
sto	71;	t/P sub R
crlf	1;	
cla	71;	
mul	76;	
out	,,051;	t
cls	71;	
mul	75;	
exp	;	
sto	70;	
cla	71;	
log	;	
mul	75;	
exp	;	
sto	69;	
cla	71;	
add	61;	
sto	71;	New t/P sub R
cla	72;	
mul	70;	
mul	69;	
sto	68;	Q sub t/P subR
add	67;	
sto	67;	
cla	68;	
mul	73;	
out	,,071;	Q
sto	2600,5;	Unit graph into 2000ff.
tix	*+1,5,1;	
txi	*+1,13,1;	
sxn	1035,13;	No. of UGOs
add	60;	
sto	60;	New $\Sigma Q$ of U.G.
cla	67;	
sub	93;	
trn	*-33;	
crlf	1;	
out	76,,052;	Pr
cls	75;	
exp	;	
mul	72;	
mul	73;	
out	,,062;	Qp of unit graph
out	60,,071;	$\Sigma Q$ of unit graph,cfs.
lxd	*+3,11;	
inp	1889,3;	Stores fc,fo, and k prediction constants + 5 constants
tix	*-1,3,1;	
halt	*+1;	Insert 1st storm data tape

lxm	1888,12;	600
lxm	1879,11;	1000
lxm	1879,10;	
lxd	*,4,5;	
inp	1895,4;	Stores 5 storm identification numbers
tix	*-1,4,1;	
crlf	2;	
out	1890,,010;	Storm identification: Location
out	1891,,020;	Month
out	1892,,020;	Day
out	1893,,020;	Year
out	1894,,022;	API
crlf	1;	
cla	1894;	API
mul	1881;	
add	1880;	
sto	1001;	1/fc
idiv	85;	
sto	1002;	fc
cla	1883;	
mul	1894;	
add	1882;	
sto	1003;	1/fo
idiv	85;	
sto	1004;	fo
cla	1885;	
mul	1894;	
add	1884;	
sto	1005;	k
cla	1004;	
sub	1002;	
sto	1006;	fo-fc
clear	1007,,15;	Puts zero in 1007 - 1021
cla	1005;	k
mul	1002;	
sto	1028;	k fc
idiv	1006;	
sto	1029;	$(fo - fc)/k \text{ fc} = C$
inp	1007;	New T
cla	1007;	
trn	*+101;	To peak and volume output
sub	1008;	[1008 = Old T]
sto	1009;	$\Delta T$
div	91;	
sto	1013;	
lxm	,6;	
inp	1010;	New P
cla	1010;	
sub	1011;	[1011 = Old P]

sto	1012;	$\Delta P$
div	1013;	
sto	1014;	$\Delta P$
tru	*+2;	
tnx	*-15,6,1;	
cla	1011;	Old P
add	1014;	
sto	1011;	New P
cla	1008;	Old t
add	91;	
sto	1008;	New t
cla	1015;	Old t'
add	91;	
sto	1016;	New t'*
mul	1002;	
sto	1017;	fc t'*
cls	1005;	-k
mul	1016;	
exp	;	
sto	1022;	e to the -kt'*
cla	85;	
sub	1022;	
mul	1006;	
div	1005;	
add	1017;	
div	1886;	
sto	1023;	$F^*$
sub	1018;	
sto	1024;	$F^* - F = \Delta F$
cla	1014;	$\Delta P$
sub	1024;	$\Delta P - \Delta F$
sto	1025;	
trn	*+9;	
sto	1026;	
add	1021;	
sto	1021;	
cla	1016;	
sto	1015;	
cla	1023;	
sto	1018;	
tru	*+36;	
stz	1026;	$\Delta RE = 0$
cla	1018;	F
add	1014;	
sto	1018;	$F + \Delta P$
sto	1027;	$F + \Delta P$
cls	1027;	
mul	1886;	
div	1002;	
add	1029;	

```

sto      1032;      -(F+ΔP)60/fc + C
cls      1005;
mul      1015;
exp      ;
mul      1029;
sto      1030;      e to the -kt'*(fo-fc/kfc)
mul      1005;
add      85;
sto      1031;      ke to the -kt'*(fo-fc/kfc) + 1
cla      1032;
sub      1030;
add      1015;
div      1031;
sto      1033;      Δt'*
cla      1015;      Old t'*
sub      1033;
sto      1034;      New t'*
sub      1015;
mag      ;
sub      1887;
trn      *+4;
cla      1034;
sto      1015;      New t'*
tru      *-22;
cla      1034;
sto      1015;
cls      1026;
trp      *+11;      Transfer for ARE = 0
cla      1026;
mul      2600,12;
add      3600,11;
sto      3600,11;
txl      *+4,13,1;
txi      *+1,13,4095;
txi      *+1,12,4095;
txi      *-7,11,4095;
lxn      1888,12;
lxn      1035,13;
txi      *+1,10,4095;
sxd      *+1,10;
lxd      *,11;
txi      *-87,14,1;
sxn      1000,14;
cla      1000;
sub      85;
add      1035;
lxn      ,14;
lxn      1879,11;
cla      3600,11;

```

sub	1020;	
trn	*+3;	
cla	3600,11;	
sto	1020;	New Max Q
cla	3600,11;	
add	1019;	
sto	1019;	New $\Sigma Q$
txl	*+3,14,1;	Is IR 14 < or = 1?
txi	*+1,14,4095;	
txi	*-10,11,4095;	
out	1020,,061;	Max Q
cla	1019;	
div	87;	
out	,,062;	volumes out
div	95;	
out	,,042;	
out	1021,,042;	$\Sigma RE$ , in.
out	1010,,042;	Total rainfall depth, in.
clear	2600,,1000;	Clears storm hydrograph stores
stz	;	
lxn	,14;	Clears IR 14
halt	*-169;	
endl	205;	

Program constants and watershed parameters

## Corn cover

7.40 0.498 2.676 .0139 1 0 7744 4096 100 .5 5 2 .9995

7.65 5.54 .75

"SPRING VALLEY CREEK WATERSHED PEAK RUNOFF RATES AND VOLUMES"

"Time, min. Discharge, cfs."

0 1000 1.426 .371 .278 .015 .142 .097 60 .05 600

## Legume-grass cover

7.40 0.498 2.676 .0139 1 0 7744 4096 100 .5 5 2 .9995

7.65 5.54 .75

"SPRING VALLEY CREEK WATERSHED PEAK RUNOFF RATES AND VOLUMES"

"Time, min. Discharge, cfs."

0 1000 0.574 .064 .428 -0.017 .097 .015 60 .05 600

Spring Valley Creek Watershed unit graph ordinates

## SPRING VALLEY CREEK WATERSHED PEAK RUNOFF RATES AND VOLUMES

7.65 5.54 0.750

Time, min. Discharge, cfs.

2.5 0.7

7.5 29.1

12.5 140.7

17.5 362.9

22.5 688.0

27.5 1086.3

32.5 1519.0

37.5 1948.0

42.5 2341.6

47.5 2676.3

52.5 2938.3

57.5 3121.5

62.5 3226.4

67.5 3258.4

72.5 3226.0

77.5 3139.3

82.5 3009.3

87.5 2846.6

92.5 2661.0

97.5 2461.4

102.5 2255.2

107.5 2048.6

112.5 1846.4

117.5 1652.3

122.5 1469.0  
 127.5 1298.1  
 132.5 1140.8  
 137.5 997.4  
 142.5 867.9  
 147.5 751.8  
 152.5 648.6  
 157.5 557.3  
 162.5 477.2  
 167.5 407.2  
 172.5 346.3  
 177.5 293.7  
 182.5 248.3  
 187.5 209.4  
 192.5 176.1  
 197.5 147.8  
 202.5 123.7  
 207.5 103.3  
 212.5 86.1  
 217.5 71.6  
 222.5 59.5  
 227.5 49.3  
 232.5 40.8  
 237.5 33.7  
 242.5 27.8  
 247.5 22.9  
 252.5 18.8  
 257.5 15.4  
 262.5 12.6  
 267.5 10.4  
 272.5 8.5  
 277.5 6.9  
 282.5 5.6

67.36 3258.44 59216.9

Sample rainfall data (input)

2 8 26 03 2.09							
195 .09	200 .22	205 .55	210 .55				
215 .62	220 .84	225 1.05	230 1.19				
235 1.3	240 1.43	245 1.55	250 1.6				
255 1.69	265 1.72	270 1.8	275 2.05				
280 2.12	300 2.21	305 2.65	310 2.8				
315 3.2	320 3.33	340 3.33	345 3.4				
540 3.57	545 3.63	550 3.68	555 3.76				
560 3.82	565 3.93	570 4.02	575 4.08				
580 4.08	585 4.13	590 4.2	595 4.25				
600 4.32	745 4.52	750 4.59	760 4.63				
765 4.78	810 4.9	815 4.98	820 5.13				
825 5.24	830 5.33	835 5.53	840 5.64				
900 5.84	-1						

2 5 25 04 .14			
30 .14	35 .22	40 .38	45 .45
125 .55	130 .85	135 .98	140 1.05
220 1.54	-1		

2 8 9 04 .21			
5 .1	75 .2	80 .35	85 .44
90 .5	95 .53	100 .59	105 .79
110 .94	115 1	-1	

2 8 18 04 .02			
5 .07	35 .07	40 .25	190 .25
195 .32	200 .37	205 .43	210 .48
215 .53	240 .56	245 .61	250 .67
255 .78	260 .88	265 .93	620 1.31
625 1.39	630 1.47	635 1.54	640 1.69
645 1.77	655 1.83	-1	

Sample runoff data (output)

2 8 26 3 2.09				
4738.9	26.00	3.40	3.40	5.84
2 5 25 4 0.14				
1049.0	2.63	0.34	0.34	1.54
2 8 9 4 0.21				
813.4	1.94	0.25	0.25	1.00
2 8 18 4 0.02				
542.6	1.98	0.26	0.26	1.83



## APPENDIX B

A sample frequency analysis will be shown for runoff volumes from legume-grass for the Sioux City excessive storms. The plotting positions were determined by the formula,

$$T_r = \frac{n+1}{m} = \frac{55}{m}$$

where  $T_r$  = average recurrence interval in years,  $n$  = number of items in the array, and  $m$  = rank of the item. For Sioux City,  $n = 54$  = number of years of record used in the analysis. Rank is established by assigning one to the largest value. See Table 6 for the numerical values.

Table 6. Sample frequency analysis

Volume (depth), in.	m	T <sub>r</sub> , years	Volume (depth), in.	m	T <sub>r</sub> , years
1.96	1	55.0	0.33	28	1.96
1.35	2	27.5	.33	29	1.90
1.29	3	18.3	.32	30	1.83
1.24	4	13.8	.32	31	1.77
1.10	5	11.0	.32	32	1.72
0.87	6	9.17	.31	33	1.67
.83	7	7.86	.31	34	1.62
.81	8	6.88	.30	35	1.57
.76	9	6.11	.30	36	1.53
.70	10	5.50	.28	37	1.49
.64	11	5.00	.26	38	1.45
.54	12	4.58	.25	39	1.41
.49	13	4.23	.24	40	1.38
.48	14	3.93	.24	41	1.34
.48	15	3.67	.23	42	1.31
.47	16	3.44	.22	43	1.28
.46	17	3.24	.22	44	1.25
.43	18	3.06	.21	45	1.22
.41	19	2.89	.20	46	1.20
.40	20	2.75	.19	47	1.17
.38	21	2.62	.19	48	1.15
.38	22	2.50	.18	49	1.12
.36	23	2.39	.18	50	1.10
.36	24	2.29	.17	51	1.08
.36	25	2.20	.17	52	1.06
.35	26	2.12	.15	53	1.04
.34	27	2.04	.15	54	1.02